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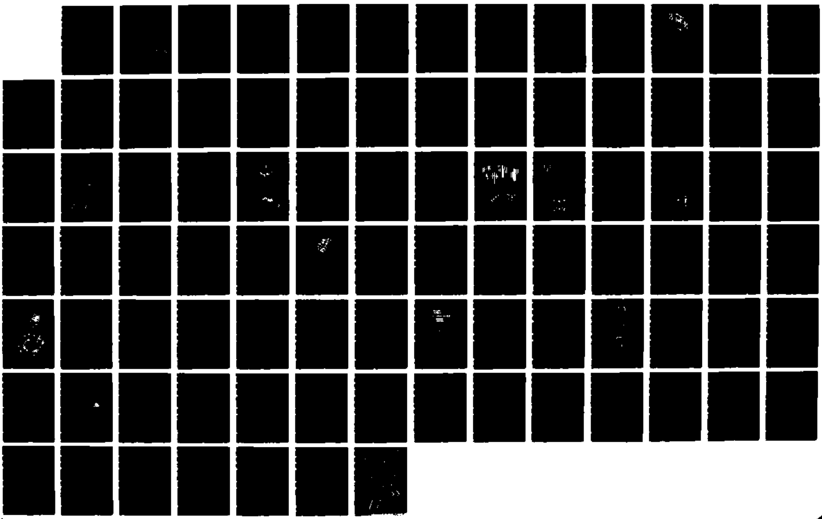

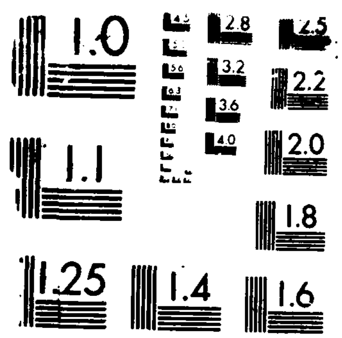

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Research Laboratory

State-of-the-Art Technologies for Construction in Space: a Review

by
Charles C. Lozar
L. D. Stephenson

Future exploration and enterprise in low-Earth orbit will most likely require space stations for support. In addition, promotion of the Strategic Defense Initiative (SDI) is mandating research and development (R&D) into technologies for building structures to serve military objectives in space. However, an assessment of the state of the art for space construction technology has revealed that the field is immature, with little conceptual and experimental research completed.

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FOREWORD

This research was conducted by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) for the Office of the Chief of Engineers (OCE) under Project 4A162731AT41, "Military Facilities Engineering Technology"; Technical Area E, "Echelons Above Corps Support"; Work Unit 056, "Construction Technologies and Methodologies for Space." The work was initiated by a USA-CERL in-house sponsored effort, "Baseline Data for Large Space Structures." Supplemental funding was provided under Military Inter-Departmental Purchase Request (MIPR) Number W31RPD-7-D4099 from the U.S. Army Strategic Defense Command (USASDC). The OCE Technical Monitor was Mr. C. D. Smith, CERD-M; the USASDC Technical Monitor was Dr. L. Blakey, DASD-CD.

The work was performed by the USA-CERL Engineering and Materials Division (EM). Architects Equities, Champaign, IL, acted as independent contractor for a major part of this study. Dr. Charles C. Lozar is president of Architects Equities. Dr. L. D. Stephenson was the USA-CERL Principal Investigator. Dr. R. Quattrone is Chief, USA-CERL-EM. The technical editor was Dana Finney, USA-CERL Information Management Office.

COL N. C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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STATE-OF-THE-ART TECHNOLOGIES FOR CONSTRUCTION IN SPACE: A REVIEW

1 INTRODUCTION

Background

Despite a major setback to the U.S. space shuttle program with the 1986 disaster, the shuttle technology represents a key element in future space exploration and research. The National Aeronautics and Space Administration (NASA) has begun to focus on the range of opportunities available to commercial and Government sectors; interests of both groups have been served in previous space shuttle missions. In addition, it has become apparent that the Strategic Defense Initiative (SDI) promoted by the Reagan administration will greatly affect military use of the shuttle.

A reusable space vehicle offers quick, economical transportation into low-Earth orbit. This potential has prompted speculation about the roles to be played by industry[1] and the Department of Defense (DOD)[2] and about the most feasible approach to exploring the solar system.[3] However, in planning a vision for the shuttle's future applications, the technology needed for constructing facilities in space often is neglected. Many of the anticipated activities will require space stations to support the mission; thus, it is critical to develop a plan for building structures in space. NASA's original goal was to complete a prototype station (Figure 1) in space by 1993; at present, 1995 may be a more realistic date.

Army requirements for facilities constructed in space are under development by the U.S. Army Materiel Command (AMC) and the U.S. Army Training and Doctrine Command (TRADOC). The need for these facilities probably will arise in the far term--1995 and beyond. The U.S. Army Strategic Defense Command (SDC), in support of SDI, probably will develop a need in the early 1990s for a structure to support the space-based primary mirror of the Ground-Based Laser system. At present, work on this structure is being given low priority in favor of other technological developments such as mirror facets preparation. However, the development of construction technologies should be at the same priority level as the other work to avoid a potential time lag when the operating systems become available.

The U.S. Army Corps of Engineers (USACE) is responsible for construction within the Army and Air Force. As such, it has provided various types of structures for a number of military requirements in several different environments--ranging from the arctic to the corrosive, hot seacoasts of the Middle East. The recent emphasis on future military activities in space means the demand on USACE's construction initiative will likely increase. To ensure responsiveness to this demand, USACE is working with NASA, DOD, and other appropriate agencies to define its role in the overall plan.

As an initial step in this direction, Headquarters, USACE, named the U.S. Army Construction Engineering Research Laboratory (USA-CERL) as the center for coordinating USACE space construction research. To meet near-term requirements and

[1] National Commission on Space, *Pioneering the Space Frontier* (Bantam Books, London, May 1986).
[2] *Army Role in Space* (National Defense University Space Symposium, 1984).
[3] *Planetary Exploration Through the Year 2000: A Core Program* (Solar System Exploration Committee, NASA Advisory Council, Washington, DC, 1983).

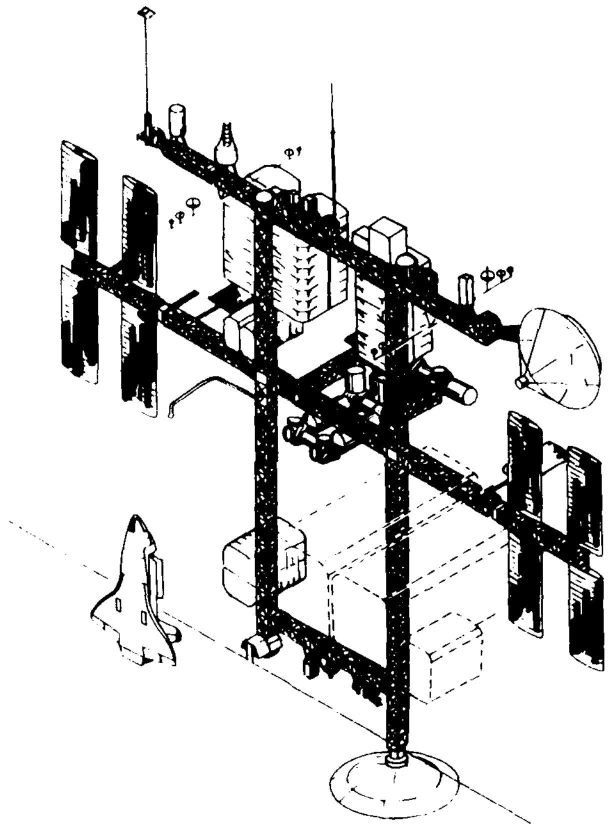

Figure 1. Dual keel space station prototype.

establish USACE's participation in new, far-reaching opportunities, USA-CERL has recognized the need to provide a solid background on state-of-the-art technology for construction in space. This background will help in defining an approach toward a potentially tremendous research mission in which USACE could be a major contributor to the new area of space-based construction methods, materials, and structures.

A topic closely related to construction in space is that of habitability factors during the construction process. In the past, the Navy and Air Force have led in habitability research due to the unique requirements of submarines and other tight critical environments. None of these environments, however, have required study at the same detailed level demanded for construction of a permanent, manned space station. Therefore, to cover the entire construction planning process, USA-CERL has included habitability factors in its work as an essential component of construction activities in space.

Objective

The objective of this investigation is to review the state of the art in space construction techniques, resources, and research directions. This information will be analyzed in terms of potential application to USACE's future role in the space exploration program.

Approach

To provide an overview of state-of-the-art technologies for construction in space, USA-CERL:

1. Searched the literature to identify significant developments in this area.

2. Interviewed research laboratories of NASA (see the Appendix), USACE, and the private sector to identify types of roles to be developed.

3. Evaluated information from the literature search and interviews to develop a management structure in relation to other Government agencies involved in space construction research.

4. Provided examples of technologies that are emerging or developing and integrated them with information from interviews.

5. Summarized each technology and highlighted main advantages and drawbacks.

6. Determined the major categories of research and most important research areas in each that would be appropriate for USACE.

7. Prepared an overview of technologies that represent the state of the art for construction.

8. Summarized findings and recommended a direction for a research and development (R&D) program supporting construction in space.

Scope

At present, there is no single collation of all technologies that might apply to construction in space. This report summarizes technologies that may have the most direct application for USACE and also related requirements for the continuing research effort. It is intended to be an overview and point the direction for focused, in-depth research.

The reader may note that some construction research discussed here appears to use approaches which are conflicting or somewhat mutually exclusive. The current construction in space research field is characterized by many different approaches; in such a new field, it is necessary to actively explore all possible sides to the problem. The configuration of the proposed space station has not been finalized and, in fact, only one real structures mission has been flown on the shuttle. Thus, many of the technologies reviewed here exist only on paper or as laboratory simulation models. The overall effect is that the research appears fragmented, with often radically different viewpoints among researchers. This statement is not in criticism of current R&D efforts, but is intended to show the great opportunity for development in this field as the Army space program grows.

Mode of Technology Transfer

This information eventually can be expected to impact technical and operational documents produced as part of the Army Space Master Plan.[4]

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[4](S) *The Army Space Master Plan*. (U)

2 MATERIALS FOR CONSTRUCTION IN SPACE

Overview

Materials research into space-related technologies is a broad, emerging field. Two major categories can be defined in this area--one comprising a large body of research that deals with materials processing in space and another dealing with materials for space in general. However, if the discussion is limited to construction materials for structures in space, the topic would become too narrow and specific for this report. Moreover, by limiting the scope to exclude aerospace materials for the construction of airplanes, the report would neglect some of the applications being transferred from the airplane sector to the space structures R&D arena.

Materials technology is emerging rapidly for application to space construction. This trend is being fostered in commercial laboratories and reflects in part the pressure from the U.S. Government to develop materials for a space station. The major emphasis is in the technology of composites, that is, hybrids of materials that combine light weight and exceptional strength. These composites usually consist of a matrix compound and a reinforcing fiber or fiber mat. Investigations of bonding, thermal stress, forming techniques, specific strengths, specific moduli, and microfracture behavior of these new materials dominate the structures applications research.

This discussion is limited to materials with the highest potential for application to construction in space--specifically, as related to trusses and space frames. Applications for habitability modules, rocket casings, and airframes are beyond the scope of this study.

Recent Technologies

Large space structures (LSS) are generally considered to be those which, in their completed state, are larger than the vehicle that carried them into orbit. USA-CERL's literature review covered recent papers published by NASA on materials technology for LSS applications.[5] Another literature search examined information available through the National Technical Information Service (NTIS). The proceedings of two conferences sponsored by the Society for the Advancement of Materials and Process Engineering (SAMPE) contain information representative of the most recent advances in materials technology. The theme of the first SAMPE conference was "Materials Sciences for the Future,"[6] whereas the other conference covered "Materials for Space--the Gathering Momentum."[7] Both conferences confirmed the emergence of a new series of technologies for space construction based on composites or related technologies. This section is largely extracted from the Materials for Space conference.

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[5]*Space Station Systems* and *Large Space Structures*, Periodic Bibliographies (NASA, 1978-1986).

[6]*Materials Science of the Future, Proceedings of the 18th International SAMPE Technical Conference*, Vol 31, J. L. Bauer and R. Dunalty (Eds.) (Society for the Advancement of Materials and Process Engineering [SAMPE], 1986).

[7]*Materials for Space—The Gathering Momentum, Proceedings of the 31st International Symposium and Exhibition*, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986).

The Materials for Space conference provided information on thermal and mechanical properties of composite materials as well as their predicted survivability; also included were methods of simulating the environmental effects of space on materials to be used in construction. In addition, information was presented on new analytical techniques for materials testing.

The major points discussed at the Materials for Space conference can be divided into three topics: (1) mechanical/structural properties of materials, (2) atomic oxygen test facilities and effects of atomic oxygen on materials, and (3) analytical methods for materials testing.

Mechanical/Structural Properties of Materials

Much of the research on mechanical/structural properties has been concerned with graphite/epoxy composites for truss structures to be used in space. Some major requirements for these truss structures are: maximum axial load of 1200 lb; thermal expansion coefficient of $\pm 0.5 \times 10^{-6}/°F$ (it is possible to fabricate composite materials with values several orders of magnitude below this[8]); nominal diameter of 2 in. (for easy handling by astronauts); stiffness of 5 to 10 x 10^6 lb/sq in. based on tube lengths of 200 and 276 in.; at least a 30-year service life; resistance to microcracking due to the 175,000 thermal cycles at ±250°F experienced by the truss tube during its lifetime in orbit; a high stiffness-to-weight ratio; and a high strength-to-weight ratio.[9] Figure 2 shows the effects of temperature on strength and stiffness as well as changes in these properties due to radiation effects.

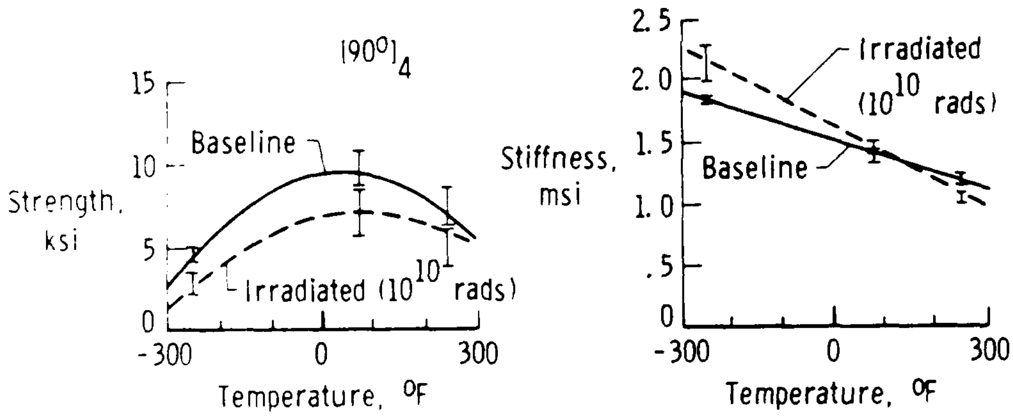

Figure 2. Transverse strength and stiffness for baseline and graphite/epoxy composites.

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[8] R. Johnson, et al., "Development of Space Station Strut Design," *Materials Science of the Future*, Proceedings of the 18th International SAMPE Technical Conference, Vol 31; J. L. Brauer and R. Dunalty (Eds.) (SAMPE, 1986), pp 90-102.

[9] D. E. Bowles and D. P. Tenney, "Composite Tubes for the Space Station Truss Structure," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 414-428; L. Leger, J. Visentine, and B. Santos-Mason, "Selected Materials Issues Associated With Space Station," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 1015-1026.

Currently, P75 graphite/epoxy-aluminum clad tubes and AS4/976 are considered to be good candidates and are projected to meet the requirements, although they are somewhat susceptible to microcracking. Graphite-aluminum composites also appear to meet all design requirements; however, high cost and current difficulty of manufacturing preclude their use.[10]

Graphite/magnesium and graphite/glass composites are among the newer materials being considered for dimensionally critical space truss components and they have coefficients of thermal expansion (CTEs) on the order of several microstrains per degree Fahrenheit with no apparent microcracking (Figure 3); nevertheless, they do exhibit a small degree of thermal and strain hysteresis.[11] A computer code called the Integrated Composites Analyzer (ICAN) has been developed at NASA's Lewis Research Center, Cleveland, OH, to predict the thermal/mechanical properties of selected composites. ICAN predicted that the P75/934 graphite-epoxy and the P100/934 graphite-epoxy composites have optimal properties for space structure applications.[12]

An interesting technique for measuring Young's modulus and damping as a function of temperature has been developed at Texas A&M University in cooperation with LTV Aerospace and Defense Company. Their method is called the Piezoelectric Ultrasonic Composite Oscillator Technique (PUCOT). Materials tested by this PUCOT include metal matrix composites, graphite polyimides, carbon-carbon composites, and powder metallurgy aluminums.[13]

This method showed that carbon-carbon composites have the highest Young's modulus at 128 GPa with a medium range damping of 0.06 to 0.4 percent. The highest damping capacity, but the lowest Young's modulus, was determined for graphite/polyimide composites at 3 to 19 GPa with 0.06 to 0.4 percent damping.

Another conference paper reported on a study conducted to compare epoxy-bonded, mechanically fastened truss joints with truss joints that had been mechanically bonded only. Both structures were subjected to thermal cycling tests. The results indicated that

[10] H. Babel, T. Shumate, and D. Thompson, "Microcrack Resistant Structural Composite Tubes for Space Applications," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 429-439.

[11] S. Thompkins, K. Ard, and G. Sharp, "Thermal Expansion Behavior of Graphite/Glass and Graphite/Magnesium," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 623-637.

[12] C. Ginty and N. Endres, "Composite Space Antenna Structures: Properties and Environmental Effects," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 545-560.

[13] R. Armstrong, A. Wolfenden, S. Vinson, and R. Knight, "Measurements of Dynamic Young's Modulus and Damping in Advanced Composite Materials as a Function of Temperature," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 372-378.

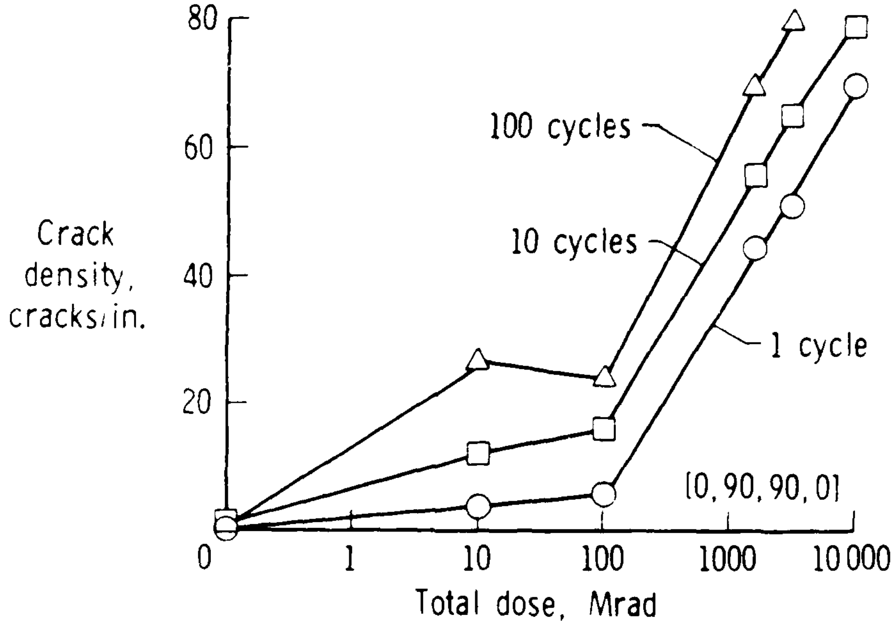

Figure 3. Effective radiation dosage on microcrack formation.

the epoxy-bonded, mechanically fastened joints were generally superior to those which were mechanically bonded only in both stiffness and strength over several thermal cycles.[14]

Ground-Based Atomic Oxygen Simulation Test Facilities and Atomic Oxygen Effects on Materials

Atomic oxygen degrades materials in low-Earth orbit. Thus, it is a special concern for structural applications.[15] The different methods for producing atomic oxygen in the laboratory can be divided into five categories as defined below along with the research group(s) using that particular technique:

1. Atomic oxygen ion beam method in which a neutralizer device ensures that only neutral atomic oxygen species are allowed to strike the sample being tested (Vanderbilt University and Martin Marietta).[16]

2. Carbon dioxide laser discharge methods in which only neutral oxygen atoms are obtained and the energy and beam flux are controlled by the energy of the laser, pulse

[14] D. Mazenko, G. Jensen, and P. McCormick, "Joint Technology for Graphite Epoxy Space Structures," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 401-413.

[15] L. Leger, J. Visentine, and B. Santos-Mason.

[16] C. Johnson, et al., "The Vanderbilt University Neutral O-Beam Facility," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 722-731.

time, combinations of inert gases, and position of gases within the reactor nozzle (Los Alamos National Laboratory and Physical Sciences, Inc.).[17]

3. Production of a negative oxygen beam via electron attachment to nitrous oxide, subsequent dissociation of N_2O^- so that $N_2O^- \rightarrow N_2 + O$, and finally, selection of O^- species and photo detachment of the electrons so that a neutral O^- beam is obtained. The advantage of this technique is that only neutral *ground-state* O-atoms are available (Boeing Aerospace Company).[18]

4. Laser vaporization methods in which cryogenically frozen oxygen/ozone films or thin films of indium-tin-oxide are vaporized via a pulse from a kryston fluoride laser (Jet Propulsion Laboratory).[19]

5. Production of low-energy neutral beams via a plasma source by neutralizing and reflecting light ions from a biased limiter device. This method also has been used to simulate material erosion by atomic nitrogen beams and combinations of atomic nitrogen and atomic oxygen. Atomic oxygen apparently has the more deleterious effect--an order of magnitude more so than atomic nitrogen (Princeton University).[20]

In all cases, the objective is to produce neutral atomic oxygen beams at fluxes of 10^{12} to 10^{15} cm^{-2} and energy of 5 eV to simulate atomic oxygen interaction with an object traveling in low-Earth orbit (such as the space shuttle) at velocities of 8 km/sec. Each technique has advantages and disadvantages. Since many of these methods are in initial stages of development, it may be wise to analyze data from a combination of these approaches to obtain the best simulation of the low-Earth orbit environment. Most materials tested to date are polymers such as polyimides and polytetrafluorethylene (PTFE).

Some metals also have been tested. Aluminum is one metal which has been found to be relatively immune to the effects of atomic oxygen and therefore is recommended as a protective coating for low-Earth orbit structures.

The mechanism by which atomic oxygen attacks structural materials in space is under investigation. A logical hypothesis consistent with most data claims that the

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[17] J. Cross, L. Spangler, M. Hoffbauer, and F. Archulete, "High Intensity 5eV CW Laser Sustained O-Atom Exposure Facility for Material Degradation Studies," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 740-751.

[18] R. Rempt, "Production of a Beam of Ground State Oxygen Atoms of Selectable Energy," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 761-768.

[19] D. Brinza, D. Coulter, R. Liang, and A. Gupta, "Production of Pulsed Atomic Oxygen Beams Via Laser Vaporization Methods," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 769-779.

[20] W. Langer, et al., "Groundbased Studies of Spacecraft Glow and Erosion Caused by Impact of Oxygen and Nitrogen Beams," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 1039-1049.

exothermic reaction resulting from recombination of atomic oxygen on the surfaces of various materials releases enough energy to break the surface bonds or to directly facilitate oxidation of the surface polymer.[21] Some researchers also speculate that a synergistic effect of ultraviolet (UV) radiation and atomic oxygen may contribute to surface erosion of polymers in the low-Earth environments.[22]

Analytical Methods for Testing Materials

Four relatively new analytical techniques may be very useful for testing composites to be used in constructing space structures. The first two methods deal with failure mechanisms of polymers. One technique uses fracto-emission, a phenomenon in which electrons, ions, neutral molecules, and photons are emitted during fracture of composites such as graphite/epoxy.[23] The other failure technique entails crack initiation and growth induced by bombardment with 10-μA, 1.6-keV electron beams.[24] The mechanism apparently involves direct scissions of load-bearing molecular chains. This technique has potential for studies in which controlled direct rupture of bonds under stress might be desirable.

Two alternative analytical techniques are more nondestructive than the latter two methods. The first method, Interfacial State Transient Spectroscopy (ISTS), is based on observing interfacial (e.g., between composite fiber and matrix) state responses to external optical, electrical, or acoustical stimuli. The response may take the form of time-resolved transient changes in capacitance or conductance of the composite sample.[25] The other nondestructive technique is a materials-oriented adaptation of magnetic resonance imaging which has been used widely in medicine during the past few years. This technique, based on magnetic resonance of the hydrogen nucleus in a

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[21] L. Torre and H. G. Pippin, "Structure-Property Relationships in Polymer Resistance to Atomic Oxygen," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 1086-1100.

[22] R. Liang, K. Oda, S. Chung, and A. Gupta, "Degradation Studies of SMRM Teflon," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 1050-1055.

[23] J. Dickinson, L. Jensen, and D. Williams, "Fracto-Emission Accompanying the Deformation and Failure of Composites and Adhesive Joints," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 390-400.

[24] J. Dickinson, M. Klakken, and L. Jensen, "Bombardment Induced Crack Initiation and Crack Growth in Polymers," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 983-992.

[25] A. Futro, "Non-Destructive Evaluation (Electronic Structure and Defects) of Low Temperature Solid State Bonding Interfaces for Advanced Materials in Space Applications," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 670-681.

nonhomogeneous magnetic field, has been shown to be useful in nondestructive tracking of selected resins during the curing process.[26]

Finally, one paper at the Materials for Space conference presented information on the adverse outgassing effects of some materials on sensitive optical devices such as mirrors, lenses, and windows.[27]

Baseline Data

The information summarized above represents a baseline for state-of-the-art materials research applicable to construction in space. As the discussion in this report progresses, it will become clear that materials and structures parameters are intimately related. The materials selection and design process involves factors that affect payload efficiency, structural stiffness, safety, and life-cycle cost-effectiveness of all systems.

Materials Processing

Low-Earth Orbit/Commercial Processing

Commercial processing of materials (inert or biological) to be transported from the Earth's surface to lower Earth orbit could be an important development for construction in space. The assumption is that beams and joints could be manufactured in space. NASA has attempted to promote this effort in the private sector in hopes of acquiring a high enough return-on-investment to pay for the shuttle flights. However, materials processing of structural members in space tends to have little advantage over Earth-based structural member manufacture and actually may have many negative features. For example, quality control and safety assurance are unrealistic, and there is the added difficulty of extravehicular activity (EVA) for astronauts. Thus, this technology is a very weak proposition at present.

Aerospace Materials

Long-running investigations have identified certain problems with using materials and surface coverings in construction of space stations. Skylab, a space station built 10 years ago, has provided some dramatic photographic data indicating very severe environmental degradation of the station's outside skin due to UV radiation, micrometeorites, and other types of penetrating cosmic dust.[28] Materials degradation is under intense study because of the long service life desired for the space station. However, most alternative materials being proposed for construction of the space station are standard products used on Earth for aerospace manufacture.

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[26] P. Frickland, "Materials Applications of Medical Magnetic Resonance," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 876-887.

[27] 1LT P. Falco, Jr., "Standardized Spacecraft Materials Outgassing and Surface Effects Measurements Tests," *Materials for Space—The Gathering Momentum*, Proceedings of the 31st International Symposium and Exhibition, Vol 18, J. T. Hoggatt, S. G. Hill, and J. C. Johnson (Eds.) (SAMPE, 1986), pp 254-261.

[28] *Skylab: Astronomy and Space Sciences*, C. Lundquist (Ed.), NASA-SP-404 (NASA, 1979).

The most important construction criteria to remember in considering aerospace materials are the limitations of the ±250°F temperature differential and severe vacuum environment. The wide temperature variation severely limits the ability to bond, connect, and mix materials in both outer space and low-Earth orbit. In addition, this variation can cause thermal structural stress and alignment problems (Figure 4). Degradation of structural members, joints, and skins is being studied as part of the space station developmental work.

Materials for Structures

In previous shuttle flights, astronauts assembled a truss-like system in the shuttle bay. This assembly is part of the Langley Research Center/MIT-developed EASE/ACCESS system. From a technical evaluation standpoint, these structural components are the only ones actually flown in space to date; these materials are discussed in detail in Chapter 5.

The selection of materials for structures is a complex issue, as will become evident later in this report. Several relationships must be explored with material behavior on LSS, e.g., the amount of rigidity achievable and the life expectancy of materials and components. The flexibility of the final structure configuration and the connection joint technology also are major factors in the selection criteria. The emphasis in materials selection for space construction technology should be on integrating the many disparate parameters into a coordinated fabrication to meet all requirements. Materials selection is discussed first since this topic applies to all other aspects of LSS construction.

Lunar Materials for Construction

Materials for lunar construction are discussed separately because of the rapidly growing interest in development of lunar surface technology. It is anticipated that certain criteria and constraints must be addressed in terms of materials processing on the moon for the construction of lunar bases.[29] Construction-related areas for lunar structures can be divided into four categories: (1) materials processing, (2) mining, (3) construction on the moon's surface, and (4) transporting lunar materials to a low-Earth orbit site for construction.

Materials Processing on the Moon

New construction technology needs to be developed if the material resources available on the moon's surface are to be processed economically for building facilities and systems. To date, there has been no indication of any substance on the moon's surface that would be economically justifiable to recover.[30] In discussions with NASA life sciences researchers in Washington, DC, it was commented that the price per ounce of bringing water to the moon's surface far exceeds that of gold.[31] Therefore, even the discovery of a precious metal on the moon would make it difficult to justify the trips for mining it.

[29] W. W. Mendel, *Lunar Bases and Space Activities of the 21st Century* (Lunar and Planetary Institute, Houston, 1986).

[30] Interview with Dr. Michael Duke, Johnson Space Center, Houston, TX, September 1986.

[31] Interview with Dr. M. Avener, NASA Headquarters, Washington, DC, March 1986.

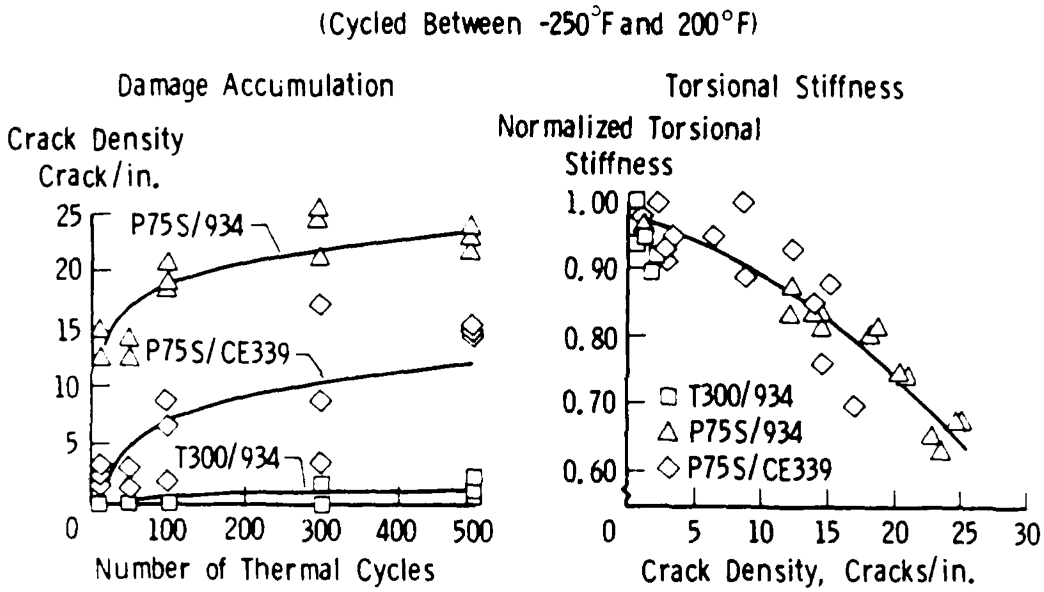

Figure 4. Effects of thermocycling on composite tubes.

The possibility of economical materials processing on the moon's surface appears questionable at present. Logically, consideration of local moon materials for construction should focus on the benefits obtainable by minimizing shuttle flights and improving payload economics. Some research has addressed lunar materials processing, but no one has focused on construction applications specifically.

Mining Operations on the Moon

Mining operations have been discussed in the literature,[32] but too little is known about the moon's surface to determine the long-term economical feasibility of lunar mining. Mining beneath the moon's surface for materials to be used in constructing human habitats is an idea with many variations. Mining operations, even on Earth, are quite dangerous. Moreover, the technology anticipated for such activities on the moon would have to protect astronauts wearing spacesuits and would have to consider any special requirements for mining under the moon's surface. Extensive use of robotics and expert systems for managing both mining and construction materials processing probably would be required. The importance of this consideration relates to the high costs for bringing construction materials from low-Earth orbit to the moon. Another approach being explored is that of using hollow lava tubes in lunar volcanic areas for retrofit habitat construction prior to human occupancy.[33]

Construction on the Moon's Surface

This issue is being investigated in depth because the possibility of using lunar materials on the surface for constructing moon habitats is reasonable. The Life Sciences Group at NASA headquarters is quite interested in the parameters and criteria for this

[32] W. W. Mendel.

[33] F. Horz, "Lava Tubes: Potential Sites for Habitats," *Lunar Bases and Space Activities of the 21st Century* (Lunar and Planetary Institute, Houston, TX, 1986).

technology and in ways of achieving this work with minimal radiation exposure to astronauts. Similar technology could be adapted for use on Mars' surface.

Current investigations of lunar construction materials are limited to evaluating surface material compositions and materials' ability to be mixed to make a form of concrete or composite material. At preser , NASA is having a contractor crush, grind, and test actual lunar materials that were brought to Earth 20 years ago; the objective is to determine construction parameters for making concrete.[34] This effort suggests some interesting possibilities for structures made of lunar materials, but there are also problems with curing in a vacuum, forming, and water supply.

It also should be noted that recovery of oxygen, metals, hydrogen, and other components of lunar rock represents a series of technologies with considerable past research. All studies have been directed toward life support, economical mining operations, or science in general, with little emphasis on the actual basics of structures for a lunar base or construction operations. Further research in this area would be beneficial because there is good potential for cost avoidance in initial planetary base missions.

Transport of Lunar Materials

A reasonable possibility is to transport materials from the surface of the moon for construction and processing in space. This concept, first suggested almost 10 years ago,[35] is based on the logic of using low-mass drivers (electromagnetic accelerator guns) to shoot moon material to a stationary orbit point called L_5. There, the lunar material would be processed into construction materials and then transported to the low-Earth orbit for use in constructing a space colony.

The basis of this concept is purely economical. That is, even after digging the materials from the moon's surface and processing them in space for space colony structural components, it is believed that the overall construction costs would be much cheaper than if ready-to-assemble components were transported from Earth. Economically, this prediction is based on the difference in costs to escape the Earth's gravity compared with that of escaping the moon's gravity. Also, the proposed mass-drivers would use free solar energy for power in contrast to expensive rocket fuel for transporting materials. Since initial development of this concept in the early 1970s, interest has declined until the possibility of further expansion is receiving only minimal support.

Research Issues

The literature search on materials for construction in space revealed several major issues meriting further review in the overall research investigation. These issues will permeate every aspect of construction-related research in space. A thorough study of these issues is beyond the scope of this work; the topics are identified briefly below to help point the way for future R&D.

[34]T. D. Linn, "Concrete for Lunar Base Construction," *Lunar Bases and Space Activities of the 21st Century* (Lunar and Planetary Institute, Houston, TX, 1986).
[35]G. O'Neil, "Colonization of Space," *Physics Today*, Vol 27 (September 1974).

Robotics/Human/Machine Interface for Construction

This area is important for its potential role in constructing lunar bases, processing materials in low-Earth orbit and other missions. Not only could robotics be more economical than human participation, but it is also logical to maximize use of robotics and artificial intelligence in accomplishing as much as possible of the construction work in a dangerous environment. This research area needs practical engineering demonstrations to support the proposed applications.

Expert Systems/Artificial Intelligence

Ten years ago, when many concepts for lunar bases and processing in space were initiated, the extent of miniaturization of computer-aided technology and its possible role in this field were not evident. Now it is clear that extensive application of artificial intelligence and expert systems for process control, layout, and feedback to operators will enhance space materials and construction development. R&D for these technologies as they apply to materials-related space construction is still in its infancy in private industry and at some NASA laboratories.[36]

Radiation/Cosmic Rays

This environmental issue has been addressed previously in terms of materials degradation, but should be reemphasized here. It also is an important point in assessing construction shelter requirements for human occupation of space--whether for inspection or processing facilities--or to allow for an evaluation of long-term human survivability on the moon's surface. This parameter relates to materials manipulation by humans under exposure to the space environment.

Cold/Vacuum Problems in Composite Materials

Use of lunar materials for construction in space would require some composite mixing. The research problem is that there are certain limitations imposed on all bonded materials because of the potential low temperature (-459°F) in space and the presence of vacuum. Based on interviews at Marshall Space Flight Center, extensive testing needs to be done on Earth in supercooled vacuum chambers to determine what types of material bonding and strengths can be achieved in a space environment for both composites and lunar aggregate-type materials.

Stability/Flexibility in Structures

When a building is constructed on Earth, any impact it sustains usually is damped by its attachment to the ground. For example, the wave action of seismic stress transmitted through a skyscraper is damped by its attachment to the ground under earthquake shock conditions. However, in space, with large structural platforms, even the docking of the shuttle against the space frame presents a potential vibration problem in that the momentum of the shuttle causes a bump to the structure and transmits an undamped wave through the structure (i.e., the structure continues to resonate in response to the initial disturbance). Therefore, structural analysis of large space platforms requires a different analytical simulation approach and needs more parameter

[36] *Extraterrestrial Processing and Manufacturing of Large Space Systems*, NASA CA-161293 (Massachusetts Institute of Technology [MIT] Space Systems Laboratory, September 1979).

investigation than would be necessary with Earth-based structures. Investigations are underway at NASA on passive control (structural damping) and active control (automated mechanical damping) of structures under vibration in space.

The transmission of the shockwave and the damping possibilities are related to the selection of truss materials and connector joints. Only one reference in the literature has been found which deals with the fabrication of a composite material tetratruss as a prototype.[37] No studies were found to deal with a comparison of material damping between composite and metallic trusses.

Materials selection for structures and vibration control are related. As the weight constraints for payload economics increase, the tendency is to use lighter, high-strength, high-modulus materials. As the lengths of structural members increase, the overall susceptibility to vibrational stress also increases and damping of the vibrations as well as control of an orbiting structure become more important, sometimes at the expense of structural rigidity. The cheapest approaches to LSS result in configurations that can be characterized as "flimsy, flexible" structures. Selecting the proper materials to reduce atomic oxygen degradation and increase LSS rigidity therefore becomes a primary consideration.

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[37] J. F. Dubel, "Fabrication of a Space Station Composite; Tetra-Truss Model," *Proceedings of the 31st SAMPE Symposium on Design and Analysis of Space Structures*, VHU513 (SAMPE, April 1986).

3 STRUCTURES FOR CONSTRUCTION IN SPACE

Most research on structures for space construction has been conducted at four NASA laboratories: Johnson Space Center, Langley Research Center, Marshall Space Flight Center, Ames Research Center, and the MIT University Space Systems Laboratory. Private firms under contract with NASA have done most of the engineering work on structures components for space stations and space platforms; large-scale contractors include Grumman Aerospace, McDonnell-Douglas, Rockwell International, and Boeing. These contractors also have been involved in developing construction concepts for the space station.

There is a direct relationship between the space station proposed baseline structure configuration and the types of beams and connectors required in terms of minimizing costs and numbers of shuttle flights. Developmental efforts for these construction technologies are in their early stages,[38] but are progressing rapidly to meet a 1995 operational target date.

NASA is now ready to contract for construction of space frames for the space station.[39] Several factors dealing with materials selection and vibration damping are discussed under **Materials Implications.**

Environmental Concerns

It is important to understand that construction of a structural frame in space must be coordinated with the space environment. Therefore, in a high vacuum environment where temperatures may range from -250 to +250°F, there are concerns for thermal expansion and contraction on opposite sides of the space frame and even within the length of the individual strut. Another problem is that sun-exposed metal may be too hot for an astronaut to touch, even when wearing insulated gloves. Atomic oxygen degradation also is of extreme concern, particularly with polymer materials. At low-Earth orbit altitudes, free oxygen combines with materials and pits or corrodes them. This process may cause deterioration and can become quite dangerous if the corrosion occurs over a long period of time at structural joints made of composite materials. Degradation of materials in orbit is best documented in early data from the Skylab Space Station.[40]

Materials Implications

As Chapter 2 indicated, materials selection and structural design are closely related. In the case of truss-frame construction for the space station, no literature to date provides a specific rationale for materials selection. Also, there appears to be no direct benefit to having a machine process structural materials in space and form them into beams or other members. This situation is due to the degree of quality control necessary in space and the present developmental level of space-related computer-aided manufacturing (CAM) robotics technology. In general, it is neither technologically feasible nor economically realistic to produce structural beams in space, according to the

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[38]*Space Station Systems: A Bibliography*, NASA SP-7056(01) (NASA, March 1986).
[39]"NASA Solicitations for Industry Comments on Space Station Design," *Commerce Business Daily* (November 1986).
[40]*Sky Lab: Astronomy and Space Sciences.*

literature and interviews with NASA officials.[41] Should a rationale be discovered for using moon materials or some other resource to construct beams in space, this technology area would merit a second look.

There may be reasons other than economics for processing unique materials in space; for instance, such technology could produce exotic types of structural materials. However, materials that have been studied by the commercial sector (e.g., immiscible metals) have not been analyzed in enough depth to determine if they have an economic structural benefit to justify manufacturing in space.

There are several other implications for materials processing in space that relate to robotics. An extensive review of possibilities for robotic manufacturing and industrialization in space can be found in a NASA report cited in Chapter 2.[42] Another publication discusses automation in relation to materials processing.[43] However, at present, no unique, clear justification has been offered for manufacturing structural members in space. Thus, for the near term, construction processes, techniques, and joint technology will relate to ground-based parameters. Most structures for space application probably will be manufactured on Earth and then deployed in space.

Literature Review

The literature was searched for information on space structures, platforms in space, and materials processing and structures in space. The topic of space structures covers a wide range of developmental aspects; however, this discussion is limited to truss-related structures and space frames.

At this point, no one structural approach appears to be favored over others for the construction of a space station. NASA's Langley Research Center has carefully reviewed the parameters, constraints, and costs of the space station to develop the present baseline configuration which has been published as an industry guide.[44] The dual-keel arrangement, truss member sizes, and joint connections are also proposed in this study.

It is important to realize that NASA is under some degree of scheduling pressure to deploy the space station and, therefore, a particular structural system will be selected very quickly. Since the initial structure is modular, it is probable that it will become a prototype for future additions to the space platform. In addition, once the space station structure baseline is refined, it may evolve into a long-term standard to avoid the high cost and difficulty of using untested components for construction. However, as of March 1987, no single structure representing the size and character of the space station truss has been flight-tested, analyzed, and mathematically simulated.

NASA's current approach uses erectable structures, with astronauts assembling the space frames through EVA. These structures achieve rigidity through joint and connector detailing. The most common strut structure being considered for space platforms is the

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[41] Interviews with Dr. M. Mikulas (Langley Research Center, May 1986) and Mr. D. Wade (Johnson Space Center, September 1986).

[42] *Extraterrestrial Processing and Manufacturing of Large Space Systems.*

[43] *Advanced Automation for Space Missions*, R. Frettas (Ed.), NASA Conference Publication 2255 (1982).

[44] M. Mikulas, et al., *Deployable/Erectable Tradeoff Study for Space Station Truss Structures*, NASA Technical Memorandum 87573 (July 1985).

combination EASE/ACCESS system developed by MIT and Langley Research Center. This structural system essentially creates a series of easily manipulated truss modules which are assembled in the shuttle bay on EVA. Shuttle flight STS-61B in September 1985 used this system as the basis for EVA testing. Although the system has not been totally configured and the issue of construction techniques for the space station is still under review, EASE/ACCESS appears to be the forerunner baseline because of its easy manipulation and previous testing on a shuttle flight.

An alternative approach is to use deployable structures such as the Delta Space Station.[45] Deployable structures are designed to "unfold" into their final configuration. Another NASA concept being developed for construction deployment and assembly uses robots and Orbiting Manueverable Vehicles (OMVs) which could assemble various structural members and also handle repair and service. A third deployable approach is to use habitability module attachments such as retrofitted external shuttle tanks to create the major space station structure. Deployable structures eventually may become cost-effective alternatives to EVA assembly. Thus, while NASA is focusing on the erectable approach for the space station, it is not completely discounting deployable options.

Yet another conceptual approach is to transport a polymer liquid from Earth and foam or form beam trusses in space. These materials could be expected to provide considerable structural integrity at a comparatively low cost. However, the literature search revealed only one related entry out of the 2000 citations reviewed.[46] This paper was entirely conceptual and did not represent an actual experiment in which the materials were tested in-flight. The quality control problems mentioned earlier would apply to this concept.

Finally, it should be noted that the material requirements for space construction may be satisfied by using the same high-strength composite materials unique to the aerospace industry. In any case, no one has proposed a benefit that would justify gravity in-space processing of microstructural members. Still, microgravity processing of materials for structural applications in space is a research area that has not been addressed in detail and perhaps could be developed in the future. At present, however, NASA's focus is on commercialization of materials with near-term economic benefit.

Structure Types

The literature search produced two works that summarize the types of structures being evaluated.[47] The rest of this chapter provides a brief overview of each type of space structure described in these two references. Additional information is available in the biyearly NASA publications *Large Space Structures* and *Space Station Systems*.

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[45] *Delta Space Station* (NASA Johnson Space Center, March 1985).

[46] P. A. Swan, "An Initial Step in Platform Construction," *Proceedings, 2nd AIAA Conference on Large Space Platforms* (American Institute of Aeronautics and Astronautics [AIAA], 1981).

[47] M. Card and J. Boyer, "Large Space Structures--Fantasies and Facts," AIAA Paper 80-0674-CP, presented at the 21st Structures Conference (May 12-14, 1980); *In-Space Research Technology and Engineering Workshop*, Vol 2, R. S. Colladay, R. A. Breckenridge, and R. A. Russell (Eds.) (Office of Aeronautics and Space Technology, 1985).

Deployable Structures

Deployable structures are generically defined as structures that fit into a small space and that are automatically or mechanically expanded or deployed from the space shuttle bay or from an unmanned rocket (Figure 5). All prototypes tend to be compressed structures that either fit inside a canister or unfold by mechanical or automated means. Many of the prototypical deployable structures have been researched to the point at which they can be deployed without the assistance of astronauts in EVA. The deployable structures used for larger frames and trusses tend to be somewhat flimsy because their load requirements are quite low; therefore, they also have dynamic shape problems. Antennas generally fit into this category as do structures which hold solar arrays for temporary deployment.

Assumptions. The basic assumption in terms of construction technology is that the deployable structure eliminates the need for dangerous and expensive astronaut EVA in assembly. Deployable structure sizes vary from small hoop-type columns about 30.5 cm in diameter used to hold solar arrays, to proposed large space-frame type structures to be used in constructing 800-m diameter antennas or space station structures.[48]

There are several problems associated with deployable structures. First, it is assumed that the structures deploy from a canister or from the interior bay of the shuttle, then as the structure is deployed, its joints, if mechanical, begin to lose rigidity due to the limits of machining tolerances. The mechanical looseness from one joint to another is amplified over the number of structural bays and, consequently, can allow a great deal of "play" in an already flexible structure. The amount of looseness or play will depend on the types and quality of joints used and may not be experienced for all deployable structures.

Another design problem is related to automated deployment of very long structures made of fiberglass rods, similar to fishing rods. When these structures are deployed, they become very flexible and can become entangled. Also, the joint configuration does not necessarily allow for super rigidity of the overall structure (Figure 6). This type of structure would be a good choice when a large or long truss-like structure mast must fit into an extremely small space;[49] however, the overall flexibility of the frame or truss would tend to limit its use in construction of pointing or focusing mechanisms.

It is difficult to simulation-model the structural efficiency of these truss-like structures and antennas--a problem compounded by the fact that inherent flexibility in the thin struts and joint connections amplifies the structure's overall flexibility and dynamic vibration. Deployable structures may be efficient in certain types of environments for specific tasks, but are difficult to vibration-damp adequately for other (precision, stable) applications.

Wrapped-Rib Antenna. The wrapped-rib antenna type structure is one in which antenna ribs are either telescoping or curled into a small canister; it can be deployed automatically. As the canister rotates, the ribs gradually unfold outward. If the antenna dish surface is to be deployed, it usually is done so separately as an umbrella-type structure. The major problem with these structures, although they use very little storage space, is that deployment does not always work as well as planned since struts and

[48] *Delta Space Station.*

[49] R. Schock, "Solar Array Flight Dynamic Experiments," *Proceedings, AAS Guidance and Control Conference* (February 1986).

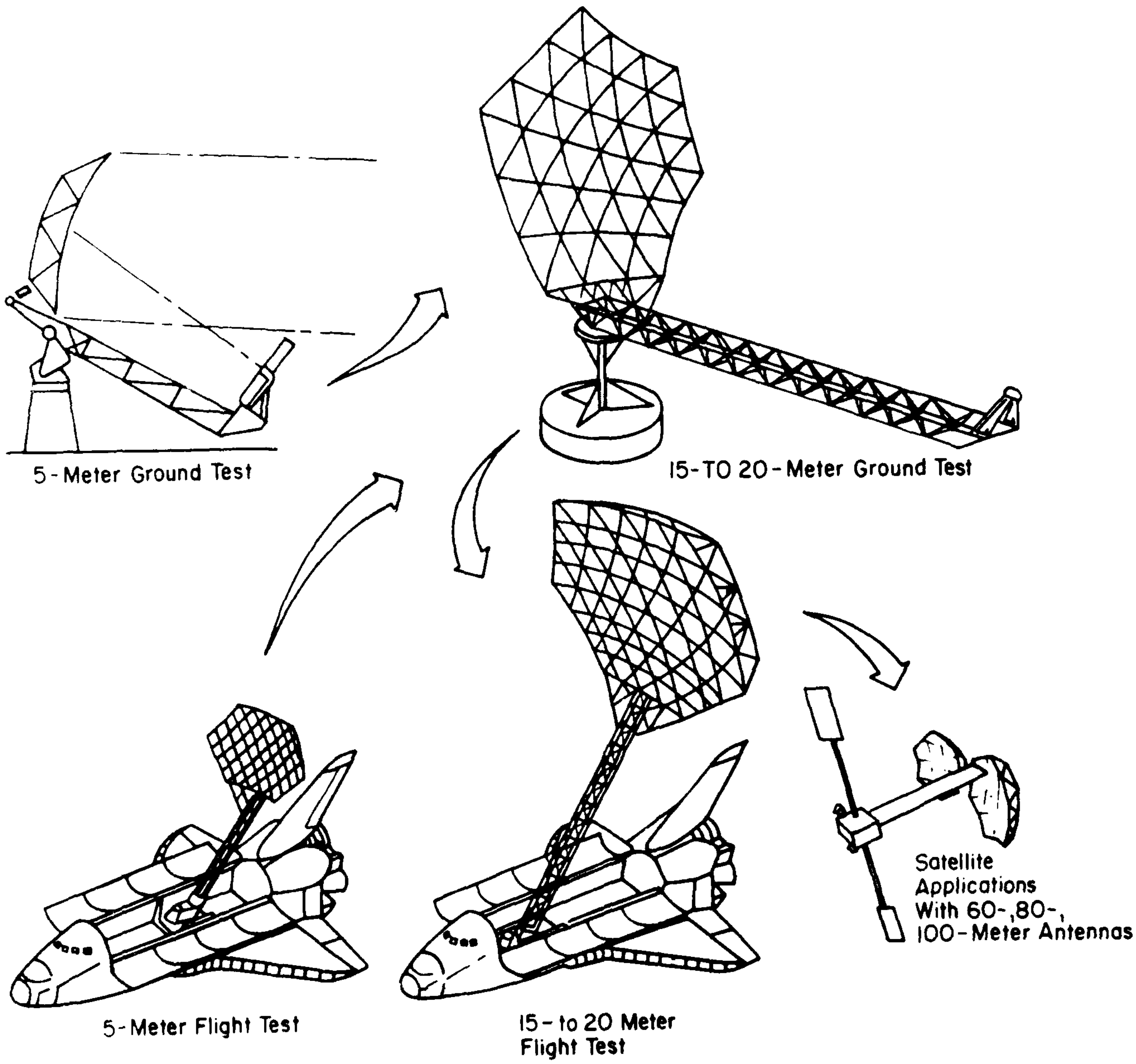

Figure 5. Example of deployable truss technology.

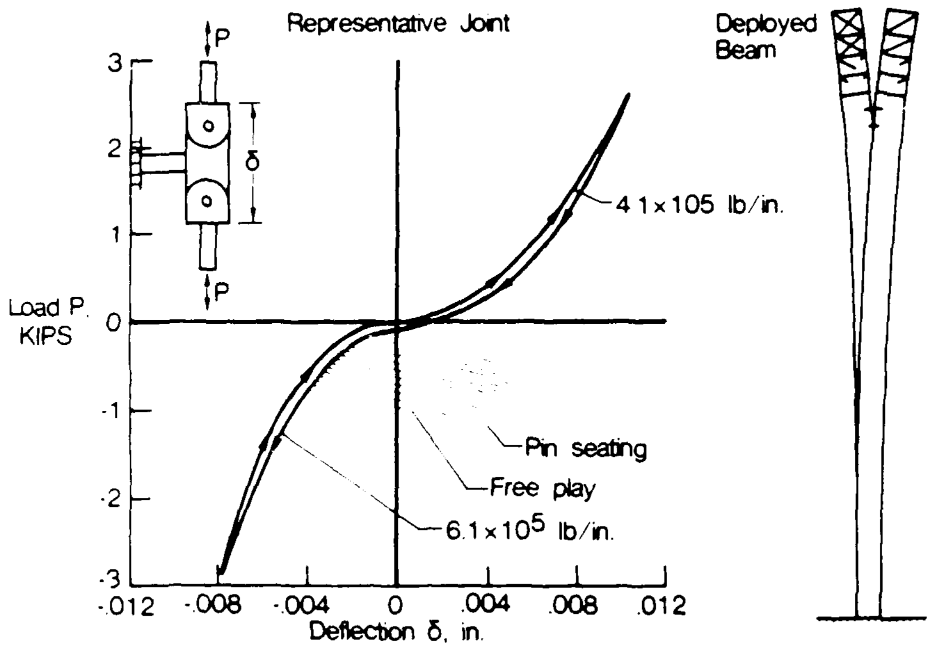

Figure 6. Joints dominate beam structural response.

tension members can become entangled in the process. Again, structural modeling of vibration and control in these antennas is very difficult and is discussed under **Structural Dynamics.**[50]

Hoop-Column. The hoop-column structure is similar to a bicycle wheel in which all members associated with the hoop are in tension at once. Generally used for large space antennas, its column portion is deployable either by telescoping rods or by a spiral-wrapped rib. The hoop-column antenna has structural modeling problems similar to other flexible systems. One design problem is in maintaining the focusing point for the antenna dish while operating an extremely flexible, vibration-prone, lightweight structure. Hoop-column application requires sophisticated engineering modeling using variations on finite element analysis.[51]

Module. Module-type deployment usually is applied to large prototype antenna structures. When the structures become so large that the inherent flexibility of truss members would allow for too much variation in the focusing mechanism, the solution is to construct several subsets of smaller dish-type antenna modules. The assumption is that, at any point in time, although the structure may be subjected to vibration, one or two of the several dish antennas will still be at the focal point. The modular approach is employed in extremely large space structures (up to 1/4 mi in diameter) where focusing and reliability are combined with redundancy so that the antenna will always be focused at the correct focal length. Control of these structures and the focusing mechanisms are covered under **Structural Dynamics.** Although several such systems have been proposed and are under study, none have been tested in-flight.

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[50] R. Freeland, et al., "Wrap-Rib Antenna Technology of Development," *Large Space Antenna Systems Technology*, NASA Conference Publication 2368 (December 1984).

[51] T. Campbell, et al., "Development of 15 Meter Hoop Column Antenna, "*Large Space Antenna Systems Technology*, NASA Conference Publication 2368 (December 1984).

Large Space Platforms. Large space platforms are essentially structures to be used in large-scale systems such as the space station. During deployment, there are special concerns for these structures when individual struts exceed 5 m in length. For example, they may inadvertently lock-up as the structure is deployed from the shuttle bay. This condition would require astronaut assistance--something a deployable structure is designed to avoid. Also, large space platforms have inherent flexibility and damping problems due to their size. In a low-gravity range above Earth, they are susceptible to vibration without damping and vibration of very low periods. Examples discussed in the literature suggest frequencies of vibration from 1 cycle/sec to 10 cycles/sec with no damping mechanisms applied.[52] For example, the Hubble Space Telescope developed at Marshall Space Flight Center has a fundamental vibration frequency of 0.2 Hz; the dual keel space station configuration is predicted to be about 0.1 Hz.

The implication is that, in LSS, a motion as simple as the shuttle docking to the side of the structure will cause a periodic wave motion throughout the structure that could continue for days since there is nothing to damp the motion (i.e., dissipate the energy of the shock). Therefore, LSS probably need both passive and active damping mechanisms along with controls.

LSS need to maintain their orbit and their azimuth positioning for focusing--conditions possibly achieved using small retrorockets mounted on the structure (Figure 7). Every time a rocket fires, a vibration and a waveform are sent up through the flimsy structure. Without damping, this periodic vibration could reach the point where it could destroy the structure on a large space platform. The problems associated with these platforms are major areas under R&D at NASA (refer to the *Space Station Systems* bibliography). Control system dynamics may, in fact, be a more important parameter than structural loadings in influencing LSS configuration development.

Reliability Concerns. Because of the tremendous expense involved in research, design, and development of structures in space, reliability is a major concern. In the case of deploying LSS from the shuttle bay, a malfunction in deployment mechanisms or spring loading, or damping of the struts, would be very expensive and would require dangerous astronaut assistance (potential energy is stored in an automated deployment mechanism).

Even if the projected reliability is extremely high, the cost-effectiveness of this approach is still questionable. In the event of an accident, the project will incur high costs of repair. In addition, LSS for deployment have damping problems for vibration and a lack of overall rigidity and stiffness throughout the structure due to the nature of the connections (see the previous section). There is also a size limitation for LSS related to the total space available in the shuttle bay. Large deployable structures could achieve their size by assembly of modules, but at some point in concept design, the ease of deployment would be overshadowed by space and weight concerns and the reliability issue.

Erectable Structures. Erectable structures are those which are assembled sequentially using individual components in space, on the surface of the moon, or in low-Earth orbit. Erectable structures are assembled by connecting struts together to form a single overall structure, usually with astronaut assistance in EVA (Figure 8).

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[52] W. L. Heard, et al., "Structural Sizing Considerations of Large Scale Platforms," *Journal of Spacecraft and Robots*, Vol 18, No. 6 (1981).

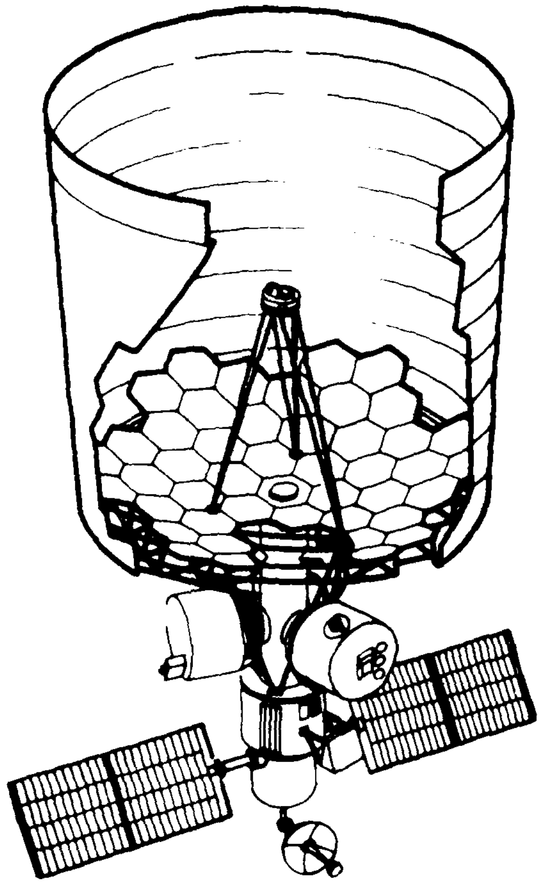

Figure 7. Large deployable reflector showing thermal shade, primary and secondary mirrors, backup structures, instrument modules, spacecraft, and solar panels.

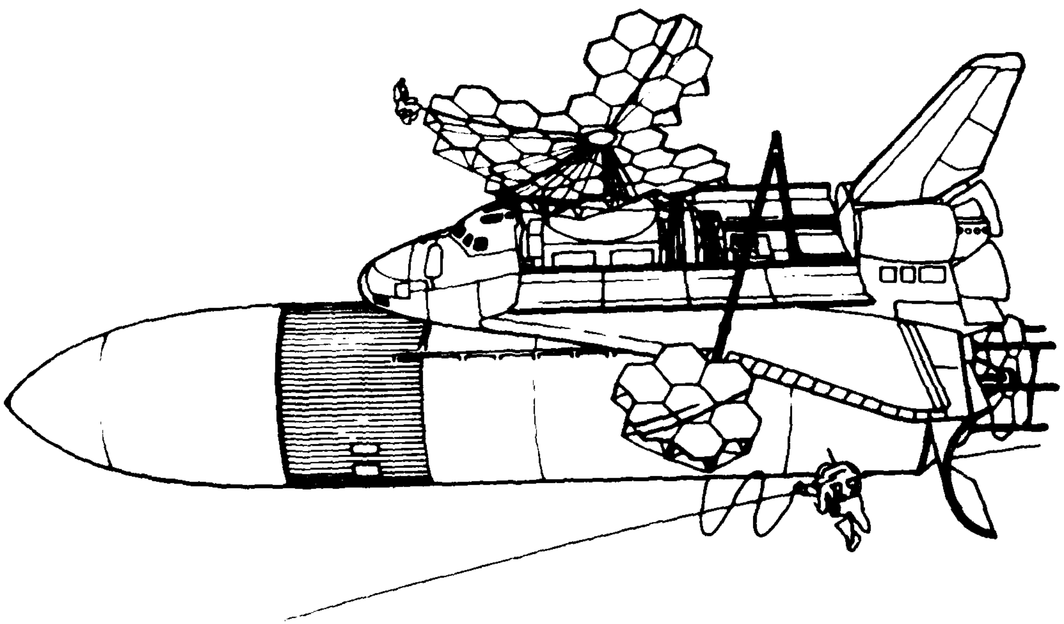

Figure 8. Assembly of large reflector telescope.

This construction approach has some problems in terms of quality assurance, inspection of completed joints, rigidity, and EVA labor associated with the installation of final utility runs. Furthermore, since astronauts are involved in the assembly of erectable structures, other issues are involved such as astronaut workload, spacesuit capability, and verification of joint continuity under the severe limitations imposed by wearing spacesuit gloves. However, it is maintained that, even at $50,000/hr for EVA, having astronauts assemble erectable structures is far cheaper than using robot-controlled, artificial intelligence automated truss assembly mechanisms.[53]

A contrasting viewpoint is that, if astronaut training and preparation costs for EVA are included in the analysis, robotic systems can be amortized faster over many structures. The cost effectiveness comparison between approaches has not been resolved and is a subject for further study.

Several pretested, erectable structure concepts are mentioned in the literature. This report focuses on five concepts with potential application to construction of a space station or other LSS.

Nesting Column Structures. An example of a nesting structure is that used in deploying truss components for antennas. The concept is extremely simple, with smaller columns nested inside larger columns. The structures are deployed by an astronaut winding a winch-type mechanism to extend the column sections. The purpose is to provide a long truss structure with minimal space required for transportation. Some problems associated with this type of deployment are poor rigidity and limitations on the final length of the nested column. Also, after the columns are deployed, they still must be joined together with connectors. Even when the assembly process is completed, complete rigidity between nested columns is not assured and therefore joints must be inspected in EVA. The nesting columns technology has been employed in single-column concepts as part of an overall test development program, based on the author's observations at Langley Research Center.

Beam Builder Machines. In the late 1970s, Marshall Space Flight Center was asked to develop an automated "beam builder." The purpose of this shuttle-borne fabrication mechanism was to construct trusses automatically in space.

The truss design was fixed as a 3-ft triangular beam. The beam builder would assemble the industrial truss members and longerons using an automated mechanism and spot-welded connections. The machine was proposed to be carried into space in the shuttle bay and operated by astronauts. The beam builder would operate either with thin sheet metal to create a very rigid truss structure or by welding together polymer-type composite structures in the same assembly format. Since polymers are susceptible to UV and atomic oxygen degradation in low-Earth orbit, it was assumed that the polymer composite structure would be covered with some sort of outer metallic surface coating for protection.

The beam builder has been operated at Marshall Space Flight Center several times for creating large beams--as long as 50 to 60 ft. However, because of the heavy weight of the assembly process machine and the need for astronaut quality control inspection, the beam builder has become a low priority within NASA. Again, interviews with NASA researchers suggested that assembly and inspection by astronauts are far more efficient than any automated type of truss assembly mechanism. However, this opinion is not

[53]Interview with Dr. M. Mikulas.

unanimous throughout NASA and, as artificial intelligence and expert systems applied to robotics continue advancing, the automated approach may become more widely accepted.

EASE/ACCESS Structural System. EASE and ACCESS are the two major erectable systems that were flown on space shuttle mission STS-61B and flight-tested in November 1985. The purpose of these experiments was to evaluate the ease of manipulating structural members and constructing truss-like structures by astronauts in space. Results were to be used in determining a baseline assembly technique for truss structures to be used on the space station. In fact, most of the joint details and strut configurations that have been tentatively selected for the proposed space station reflect an expanded version of the positive results from the EASE/ACCESS experiment.

As part of the experiment, MIT Space Systems Laboratory had been contracted by NASA to evaluate human factors--especially productivity and efficiency in assembling the structural truss. The two approaches were studied separately (EASE and ACCESS) because they differ both in scope and complexity. ACCESS, which was developed by MIT Space Systems Laboratory involves an astronaut-assembled, triangular, large space truss of extended length--up to 45 ft. It is constructed of 10 identical bays consisting of struts and nodal joints located in three storage canisters on the assembly support (called the MPSS--Mission Peculiar Equipment Support Structure) of the shuttle. Ninety-three tubular aluminum struts, each 1 in. in diameter, and 33 nodal points are used to complete the entire structure. After the tests, astronauts reported that it is easy to assemble and disassemble this structure. Part of the reason was said to be the efficiency of joint and connector assembly and the fact that manipulation of the lightweight structural components in space required very little physical effort.

The EASE experiment, designed by Langley Research Center, required larger structural components than did ACCESS. Six aluminum beams, each 12 ft long and weighing 64 lb, were connected as a pretest for ease of assembly in creating a geometric framework as a possible alternative for the space station truss. Two astronaut mission specialists worked together to unstow the beams and prepare the joint details for final assembly.

Both EASE and ACCESS[54] were pretested for assembly time, ease of assembly, and joint connection rigidity using the Marshall Space Flight Center underwater simulation (neutral buoyancy) test tank. Final testing and verification were done at Johnson Space Center, which also has a simulation tank. The MIT report showing results of the simulation tests on efficiency and time allotted astronauts for onsite erection of space structures serves as a baseline for productivity in erectable construction productivity analyses.[55]

Connecting Joints. Several different types of connecting joints have been proposed for erectable structures. The major guiding criterion is ease of assembly by astronauts working in tightly inflated spacesuits that allow only limited finger movement. It is critical to ensure that the strut joint is made tightly so that maximum rigidity is achieved for the completed assembly. Although these requirements do not appear too stringent, many joint problems have plagued manipulation and erectability of space structures. The physical connectors must be rigid, of simple design and operation, and designed for a service life of 20 to 30 years in low-Earth orbit.

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[54] *EASE/ACCESS: Post Mission Management Report* (NASA, 1986).

[55] D. Akin, et al., *EVA Capabilities for the Assembly of Large Space Structures* (MIT Space Systems Laboratory, October 1982).

The most advanced and highly tested concept was developed at Langley Research Center. This joint consists of a clasp-type structure that joins two struts together and a twisting mechanism that inserts a lockable key into one of the two components. This device is a baseline candidate for the final joint design to be selected for the space station, although individual aerospace contractors will be allowed to vary the design according to their own adaptions.[56]

Space Station Truss Structures. Based on the early EASE/ACCESS experiments and the NASA baseline specifications for structural performance, individual contractors who are bidding on the space station project will be required to develop the baseline truss structure. The space station will espouse a dual-keel approach as promoted by NASA in its RFP of May 1986. This configuration originally was chosen because of its rigidity and ease of assembly; however, even the baseline specifications are still under development. NASA is now considering a simplified structure for better economics.

The actual keel configuration of the original truss structure is a square, box-type, 15-ft frame. This configuration allows structural rigidity as well as ease of assembly with visual orientation in space, which will be important to the astronauts during construction. Also, because it has modular squares on each side, the structure is easily adaptable to a mobile Manipulator Robots System (MRS) which is proposed to automatically crawl along the truss side to service satellites and other equipment. Finally, because of its overall rigidity, each module or bay of the truss structure, 5 m on a side, creates long tunnels through the truss. This feature would permit astronauts to travel from one end of the truss structure to another and maneuver with some degree of safety. Also, by having standardized modules, any attachments to the truss can easily be made by various manufacturers. The selection of this configuration is based on extensive engineering studies done at Langley. The report on this comparative analysis covers launch weight, structures, dynamics, and final economics.[57]

Several configurations for the space station are still under study and by no means is this truss structure the final choice (Figure 9). So far, however, NASA has indicated that most potential contractors favor the configuration developed at Langley.

In developing a space station, it is essential to address the vibration and control problems associated with atmospheric drag, pointing and orientation, vibration and control, docking, and even vibration from astronaut movement within the habitability modules. These issues are of major concern to NASA and will be evaluated during the actual assembly of the prototype space station. The structure will undergo many tests during assembly by the astronauts before habitability modules will be allowed to be occupied. In general, however, the proposed erectable space station structure is stiffer and has fewer vibrational problems than the alternative deployable structures discussed earlier. A possible exception to this statement is the Delta Space Station concept, which achieves rigidity through its triangular shape (Figure 10). Although a space station baseline has been documented, NASA is *not* eliminating other geometrics from consideration. Alternative configurations may offer better economy, depending on the specific application.

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[56] M. Mikulas, et al.

[57] G. Nurre, et al., "Dynamics and Control of Large Space Structures," *Journal of Guidance*, Vol 7, No. 5 (1982).

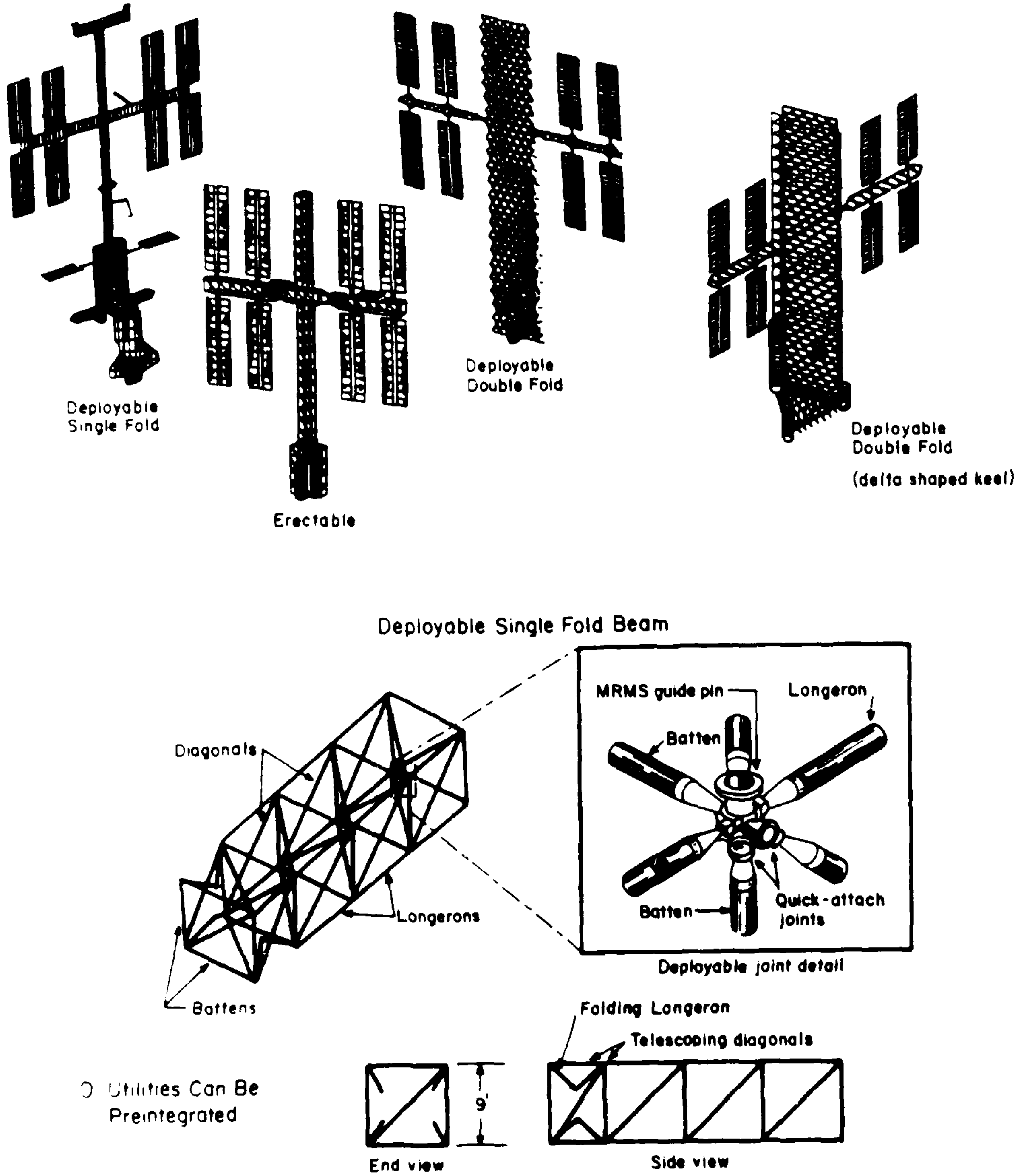
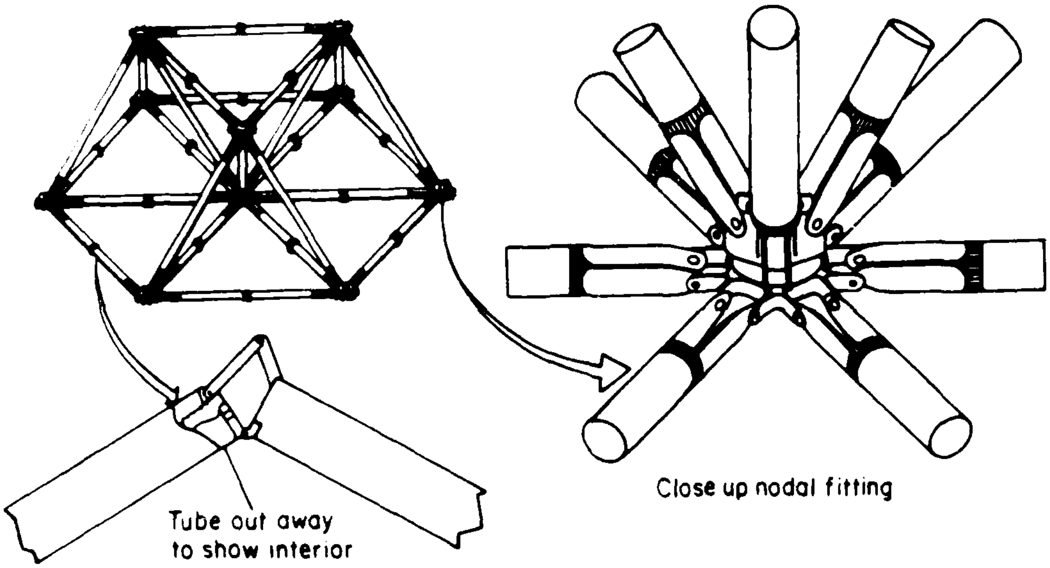


Figure 9. Space station configurations and joints.



Deployable Tetrahedral Truss

The torsional and bending stiffnesses of the diagonal and the foldable struts (ignoring joint tolerances) force nodes to remain parallel and restrict joints to deploy together

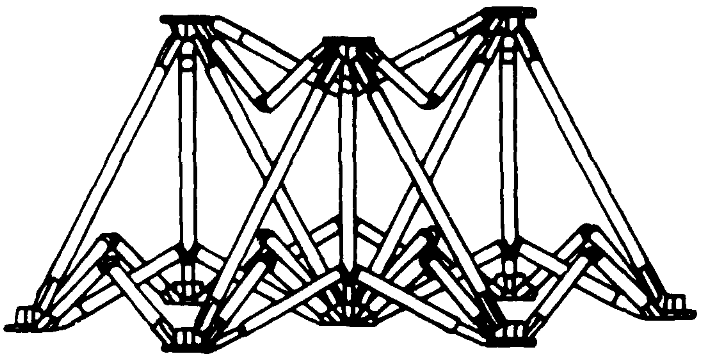


Figure 10. Example of a deployable tetrahedral truss.

Structural Dynamics

Flexible Structures

The structural dynamics of LSS is a matter of extreme concern to all parties involved in developing the space station, and other LSS such as antennas. In terms of design, the primary concern stems from a relationship between several factors, one of which is the need to minimize weight as a structure is carried aboard the shuttle into low-Earth orbit. This requirement implies very efficient structural frames such as trusses in which individual components have very low mass. To minimize weight, some members have been designed to be as small in diameter and as thin as fishing rods; other sections are more like thin-gauged aluminum sheet metal.

Because there is no appreciable gravity in low-Earth orbit, the only purpose of the truss is to maintain desired overall structural rigidity by geometric form and to connect various habitability and experimental modules in proper configuration. Because of this interrelationship between lack of gravity and minimal material to reduce launch costs, the structures may tend to be very flexible. The result is an unusual design condition for which, even with finite element analysis, the flexibilty of the structure itself is both difficult to model and to simulate mathematically. Very small loads may cause the structure to vibrate unaccceptably.

Many of the assumptions made about the structural modeling criteria are not valid when gravity constraints are eliminated. Some structures require very little stiffness and are designed only to maintain necessary adjacencies between components in space. Other structures, such as telescopes with mirrors and large antennas, require moderate degrees of stiffness to maintain the focal lengths. Because of these variations, there are several possible alternative approaches to damping vibrations in space.[58]

For buildings on Earth, the environment provides significant damping and dissipation of structural vibrations. Major environmental factors include the soil-structure interaction and the frictional resistance of structural joints and connections (this resistance is greatly enhanced by the gravitational forces on Earth). However, for large "floating" structures in space, gravity is negligible and there is no natural phenomenon external to the structure to dampen vibrations; thus, a waveform period from a shock could continue almost indefinitely.

Vibration and Periods

If the structure is extremely flexible over an extended length, then the period of vibration could be very low and it could be expected that the waveform traveling back and forth through the structure would continue for a long time or might eventually resonate and destroy the structure. The design questions then become: (1) how to mitigate this vibration before it becomes dangerous to the structure and its function and (2) how to dissipate the energy involved with the mitigation.

These concerns highlight the problems involved in structural modeling and mathematical simulation for this type of structure (Figure 11). No comparable structure

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[58] G. Nurre, et al.

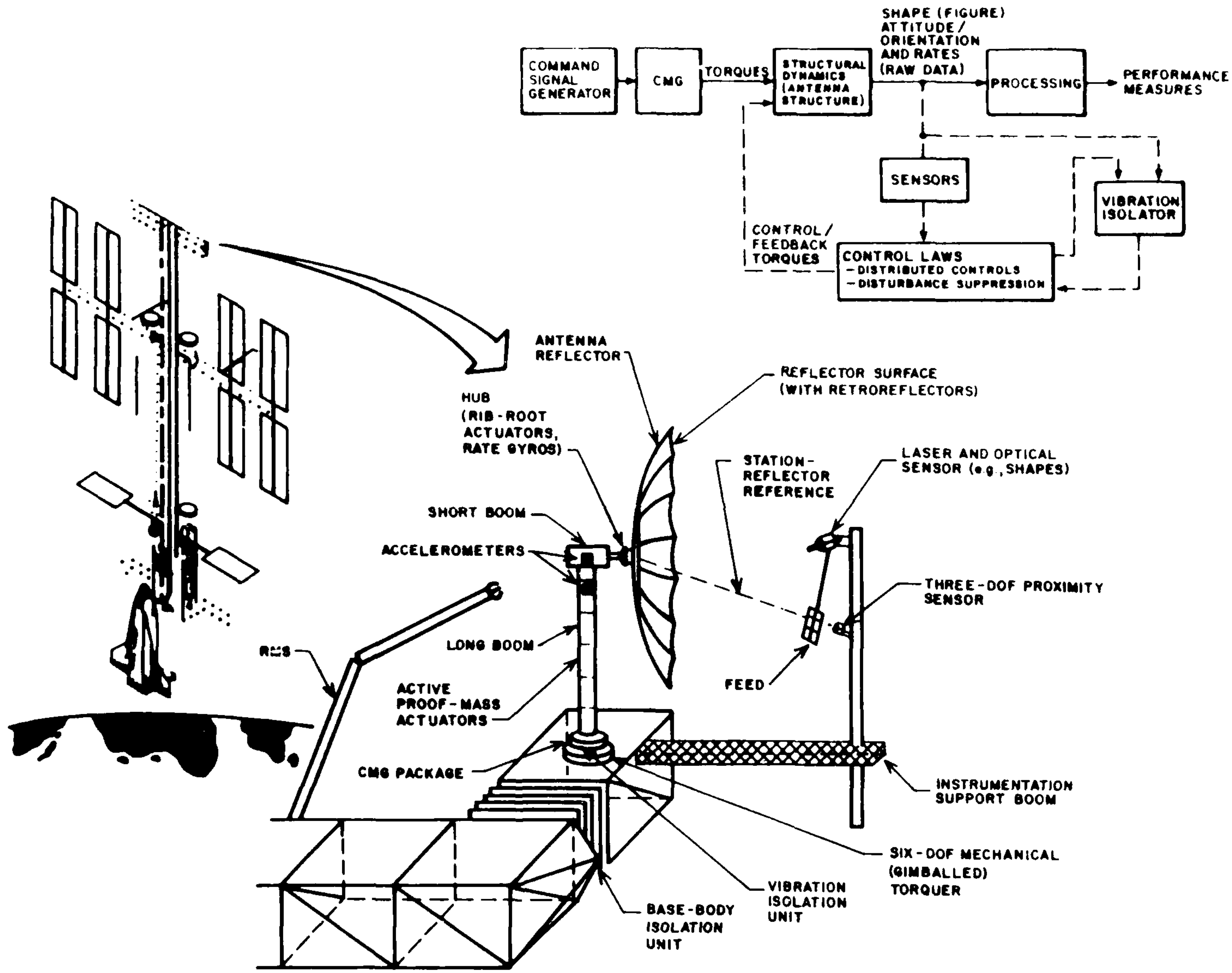

Figure 11. Example of a dynamic disturbance experiment.

can be built on Earth to study as a model. This lack of low-gravity simulation capability makes structural verification impossible. The assumption is that Earth-bound, passive mathematical models cannot be used to reliably simulate this behavior.[59]

Damping

Damping is the process of dissipating the vibrational energy in a low-Earth orbit LSS to stop vibration or destructive waveforms throughout the structure. Two common methods are being considered as potential solutions for this problem: passive vibration control and active damping. Both methods still require further study for application to various types of structures.

Passive Vibration Control One method of passive vibration control works much like the shock absorbers on a car. Instead of having solid struts at a number of points throughout the structure, there are essentially shock absorber struts placed within the structure. Vibrational energy, e.g., from a shuttle docking with the space station, is dissipated into a fluid inside the shock absorber, and is then dissipated as heat into space through radiators attached to the shock absorber. This is a unique concept since there is very little comparable structural analogy in construction technology for structures on Earth.

Active Damping. This concept is being studied extensively by NASA and private contractors. The active damping approach is to mitigate vibration throughout the structure by actively attempting to stop it. This action occurs through the use of sensors that detect a passing waveform of energy or motion in the truss structure and actuators that apply a counterforce or tension to, e.g., a wire member.

These types of active control systems attempt to "stiffen" the structure by automatically sensing the waveform, resisting it, and thereby damping the motion throughout the structure. Another method of active damping uses momentum-type actuators consisting of devices that sense motion in the structure and solenoids that send out a counteracting vibration to cancel the original shock wave. These active damping actuators require sensing mechanisms, immediate computer simulation analysis and response, and instructions similar to those for artificial intelligence to cancel the motion effectively.

As an example, consider a very long, flexible, extended beam. It could require 10 to 15 of these active mechanisms positioned at various points. If the beam members are very small, then the total mass of the actuators positioned on the beam or truss could exceed that of the truss structure; at this point, the optimal control relationship has been passed. That is, now the mass of certain actuators will be counteracting the motion of the mass of other actuators, which originally had been intended to counteract the waveform propagating through the truss. Modeling this type of structural waveform activity in a large space truss using mathematical simulation is still under study.[60]

Modeling Structures

The foregoing discussion makes it clear that the modeling of structural concepts for vibration and control in space is very different from modeling anything comparable

[59] R. Ryan, *Problems Experienced and Envisioned for Dynamical Physical Systems*, NASA Technical Paper 2508 (August 1985).

[60] Interview with Dr. Henry Waites, Marshall Space Flight Center (April 1986).

on Earth. It is also apparent, that since gravity affects all masses on Earth, it is impossible to create an analogous simulation model for generalizing concepts as they exist in space. Therefore, NASA has proposed a flight experiment (SAVE: Structural Analysis and Verification Experiment) to deploy a large space truss structure complete with momentum actuators and beam-type sensing mechanisms to verify certain mathematical models that have already been developed.[61]

Deployment of this truss structure will provide a baseline concept model for researchers studying LSS. There is much research emphasis on the mathematical modeling of this structure given the target date of 1995 for deployment of the space station. Contractors attempting to select space station components are especially interested in verifying control and simulation concepts. Also, as space antennas for SDI become larger and larger, it is essential to be able to model the structural dynamics of large, flexible structures for verifying that the required shape can be maintained.

Marshall Space Flight Center has developed the CONTOPS Modeling Program[62] for beginning analysis in this area. However, this topic requires a large amount of research and mathematical innovation before some of the questions can be resolved.

Structural Materials Applications

Overview

Among the present concerns with selection of materials for structures in space, those for rigidity and degradation overshadow all others. Structural rigidity must be related to the cost of transporting materials into space. On a cost-per-pound basis, carrying materials into space is now estimated at about $4000/lb. Thus, a lightweight material is sought that will ensure the structure's efficiency in terms of rigidity. Much of the R&D is focusing on super-stiff strut materials to minimize weight and cost.

The second area of major concern is degradation of structural materials in space. Degradation occurs in two ways. The first is through exposure of materials to radiation, primarily solar. No analysis has been done on materials returned from exposure in space to test the effects of radiation on the strength of structural components. Several studies have dealt with coatings in environmental degradation, but none specifically deal with structural load capacity degradation.

The second way materials degrade is through exposure to atomic oxygen. At the altitudes of the space station and large antennas (i.e., low-Earth orbit), there is an abundance of single-atom oxygen. Oxygen is a very active element even in diatomic form; when it exists as a single atom it has an even greater tendency to combine with other materials to form compounds. Of the materials being considered for construction in space, polymers are the most susceptible to atomic oxygen degradation. At the same time, they also are good candidates for truss structural materials. Thus, a paradox exists in terms of selecting materials with a reasonable economic life in low-Earth orbit space in that the best candidates apparently are the most susceptible to degradation.

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[61] *Control of Flexible Structures (COFS) in Space Research*, Vol 2, Technology and Engineering Workshop, (Office of Advanced Science and Technology [OAST], October 1985).

[62] *A Control System Simulation for Structures With a Tree Topology (CONTOPS)*, 486-11424 (Honeywell Space and Strategic Avionomics, April 1986).

Aluminum Structures

To date, most components for erectable space structures as well as those assembled by the Marshall Space Structure Beam Builder are made of aircraft-quality aluminum alloys. Atomic oxygen degradation of these alloys is generally considered to be minimal. Furthermore, aircraft quality control standards are used to predict structural strength and stiffness. The space station components developed at Langley consist of tubular aluminum alloy, about 1-3/4 in. in diameter, with machined aluminum alloy connector joints. Thus, at present, aluminum components are more likely to be used for space station structural members than polymer-composite materials.

Composite/Aluminum Structures

A recent development at Langley is a graphite-epoxy strut made in an unusual way. The graphite epoxy is laid on a thin aluminum tube shell which is about 2-1/2 in. in diameter and about 15 ft long. The graphite fibers follow the length of the tube and the polymer compound used as the matrix is applied over the graphite. An outer shell of aluminum tubing is placed over this structure, thereby creating a double-shelled aluminum protector for the polymer matrix holding the graphite strands. The assembly is then heat-cured. The outer shell is chemically etched so that the resulting outer aluminum wall thickness is a few thousandths of an inch. The outer shell is also anodized, providing adequate protection from atomic oxygen. This type of strut member has not yet been tested in a shuttle flight.[63]

Metal Matrix Composites

Polymer Systems

Polymer systems for large space structures are primarily being studied at Marshall Space Flight Center and Johnson Space Center. Polymers would allow many possible variations in terms of extruding, assembling, and welding beams together in space. However, other than using a protective coating, no method of retarding degradation has been discovered for any polymer system.

Space Certification

The literature and discussions at Marshall and Langley have indicated there is a specific term describing the certification of various materials and components for use in space. "Space-certified" means that the material and the assembly have been tested extensively and evaluated, qualified, verified, and approved for reliability before becoming part of the shuttle flight structure for which it is intended.

The term "space-certified" also indicates that all inspection tests and tracking through a series of quality assurance steps have been done on a particular component. For permanent structures in space, each truss member, for example, will be tracked by a specific code number and paperwork documenting structural evaluation from the time it is manufactured until it is finally deployed in low-Earth orbit. Space certification indicates that the material has met quality standards and has received extensive reliability testing.

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[63]Interview with Dr. M. Mikulas.

The paperwork and tracking, although cumbersome, are necessary because of the cost of deployment in space and the cost and danger of retrieval or repair in a hostile environment. Space certification will require extensive effort by the designer, who will need to allow extra time for this process. Since the design of new structures usually takes a long time, any research in this area should allow adequate time to develop the experiment into a form feasible for implementing on a shuttle flight. Space certification can add tremendously to the overall cost of a mission, but is nevertheless an inherent part of R&D and flight-testing.

Large Space Structures (LSS)

EVA Assembly

In developing assembly techniques for LSS, two primary constraints must be considered. The first is the astronaut's limited ability to manipulate structural members. As mentioned earlier, the configuration of the SAVE experiment uses 5-m members and has holding fixtures for EVA torque application, along with foot restraints for the astronauts. Current erectable structures do not overcome this limitation for EVA. However, work by Johnson Space Center on geodetic members with lengths up to 300 ft is promising, so that the concept of EVA-assisted assembly could be reevaluated for extremely large beams.

The second constraint is construction joint design and its impact on assembly procedure. That is, as the structure becomes larger and larger, the joint internal flexure begins to interact with the bending in the strut member as both length and stresses increase. The possible outcome of this interaction in a flexible LSS is joint-dominated structural performance dependent on a loosely connected series of individual members. Tolerances between joints (as manufactured) also can have major impact on performance as structures become larger. These conditions probably would be true for both deployable and erectable structures. Assembly problems for LSS are more thoroughly reviewed in a NASA publication.[64]

Structural Loading in Transport

The stresses and shocks associated with manuevering and orienting LSS may be the largest load that the assembled structure will receive over its space-use lifetime. However, launch condition stresses on members held in assembly racks in the shuttle bay can reach 8 to 12 Gs, with accompanying vibrations in the rack; these stresses may be the maximum to which the individual components will be subjected. A paper by Dahlgren analyzes this area[65] and further discussion can be found in any of the conference proceedings cited in the **References.**

Space Stations

This report has so far discussed the space station as if it is a single structure being developed to serve all possible functions. In reality, there may be commercial merit in having many different types of space stations with various structural concepts and

[64] *Analysis of Large Space Structures Assembly*, NASA Contractor Report 3751 (December 1983).

[65] J. B. Dahlgren, *Pointing and Control System Technology for Future Automated Space Missions*, #79-23 (Jet Propulsion Laboratory, December 1978).

approaches. A separate publication deals with the advent of civilian space stations and discusses their possible purposes and economic benefits.[66] While the reader should recognize that other structures are possible, this report emphasizes the construction approach, methods, and baseline configuration being developed by NASA for the prototype space station. Near-term construction problems are the most relevant in light of NASA's space station objective.

Moon Structures

The recent book by Mendel (see Chapter 2) on lunar base construction probably contains the best overview of creative thinking to date in terms of research on moon structures. The USACE document referenced herein lists some of the early conceptual objectives for constructing a moon installation, but the Mendel book updates and expands this information with knowledge gained over the last two decades. Mendel covers lunar base concepts, transportation issues, science, construction, and industrial processing.

Concrete Structures

As mentioned in Chapter 2 on materials, concrete structures made of moon surface materials is a lunar construction concept under investigation.[67] However, the problem of actually constructing a liquid matrix in a vacuum to bind together the moon material aggregate (probably basaltic rock) has not been addressed. It is necessary to identify a type of liquid that would neither evaporate in a vacuum nor freeze solid at -270°F before it has a chance to set. One suggestion has been to use polymers that harden upon exposure to UV radiation, but this concept has not been proven successful for making concrete. In summary, application of a locally produced concrete in moon construction has not been resolved adequately. It is important to note, however, that this issue is being studied with respect to real construction applications.

Processing Materials for Moon Structures

The literature search revealed no structured, detailed approach for processing materials to be used in construction of facilities in space. There have been suggestions of material types and speculations on the adequacy of oxygen and hydrogen for fuels on the lunar surface, but no documentation of high-vacuum testing to determine the hardening properties of composite construction materials on the lunar surface. Further, there are no developments reported on the application of automated machinery with artificial intelligence to enhance such processing on the lunar surface.

Alternative concepts for lunar construction range from concrete beam structures to the use of existing lava floor tunnels and, more realistically, use of expended shuttle external tanks for the first moon-based habitats. The important thing to understand in

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[66] *Civilian Space Stations and the U.S. Future in Space*, OTA-STI-241 (Office of Technology Assessment, November 1984).
[67] T. D. Linn.

every one of these concepts is that the overriding concern is radiation protection from solar flares for humans living and working on the lunar surface.

Moon-based construction is beyond the scope of this report; however, because of the possibility of space industrialization and dependence on the moon as a resource base for orbiting colony construction,[68] lunar construction has been included to show its potential over the long term.[69] From earlier comments about flight-testing orbiting structures, it should be clear that pretesting moon construction technologies and quality assurance for safe human habitation are the overriding problems in researching this area.

Research Opportunities in Space Construction

Research opportunities can be identified for a number of topic areas related to space construction. Included are the materials, structures, lunar bases, tools, and automation fields. Further, very near-term opportunities are associated with NASA's emphasis on deploying a prototype space station. Research into construction parameters is probably one of the most immediate areas of concern. Research opportunities in structures are described in detail in Chapter 7.

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[68] G. O'Neil.

[69] *Space Settlements: A Design Study*, R. Johnson and C. Holbrow (Eds.), NASA SP-413 (1977).

4 AUTOMATION FOR CONSTRUCTION IN SPACE

Rationale

The rationale for using automated systems for construction in space should be clear. Space is a dangerous, hostile environment, and use of automated "intelligent" machines to do repetitive tasks could avoid exposure of astronauts to this hazard. In addition, astronaut labor in space is very expensive when the costs of training and preparation are included. Some researchers assume that automation of certain functions would reduce these costs.

These conditions have promoted the development of several conceptual automated construction methods. These technologies are in various stages of development, but the focus over the next 10 years will likely be on space station applications. Within the R&D community, there are conflicting opinions over the advantages of automated construction systems versus astronaut EVA. This controversy probably will grow once analyses are completed comparing the intrinsic training costs for EVA-assisted erectable structures with those of developing automated intelligence for robotic assembly.

NASA has published an overview of automation and robotics as applied to the space station.[70] This report covers spacecraft servicing, structural assembly, contingency events, and relationships to technology requirements. Another NASA report deals more generically with a wide array of robotics and machine intelligence application to space missions.[71] The second study deals intensively with the programming needs for automated space manufacturing and self-replicating lunar factories.

Automated systems range from robotics to artificial intelligence and expert systems. Aspects of such systems must be considered in developing automation for construction in space. An important step in the R&D is to make a detailed analysis of the cost-effectiveness of structural assembly in space. Any automation configuration that attempts system-type assembly must be analyzed for the cost-effectiveness of both time spent in space and payload weight. This chapter reviews some of the work done to date on automated systems.

Applications for Construction

There are several evolving research technologies that could use automation and robotics for construction in space (Figure 12). However, the actual process of construction in space is in its infancy. For the most part, robotic construction technologies are for pretesting structural assemblies on Earth and shipping them into space via rockets or the shuttle.[72] Little actual work has been done for automated construction in space, compared with the total amount of research effort expended for space travel.

In the R&D of these systems, an unresolved question is that of what would be cost-effective to construct robotically in space. It is reasonable to predict that components

[70] D. Akin, et al., *Space Applications of Automation Robotics and Machine Intelligence Systems (ARAMIS)*, NASA Contractor Report 3734 (October 1983).
[71] *Advanced Automation for Space Missions.*
[72] *EASE/ACCESS, Post Mission Management Report.*

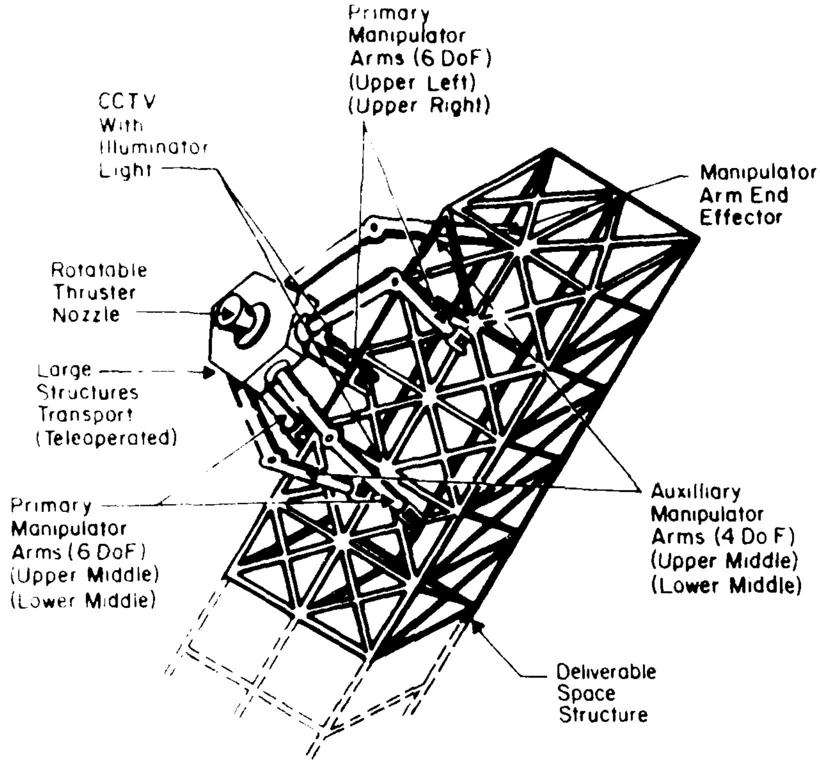

Figure 12. Dynamics of **retargeting and maneuvering large structures.**

most likely to have a fast payback are those which are commercially viable now (e.g., telecommunications antennas). In addition, military applications that use focusing mirrors, telemetry, and radar are included in SDI.

Construction methods, procedures, and critical path assembly methods for structures represent a very small fraction of space research data developed over the past 25 years. Thus, robotic assembly of structures and devices in a space environment is an area open for innovation. The application of automation and robotics to construction in space can be expected to grow rapidly as artificial intelligence and expert systems become refined.[73]

Cost-Effectiveness

Considering the high cost of astronaut labor, it may appear that automated robotic fabrication in space would cost less than assembling components made on Earth. However, Mr. G. Hall at Marshall Space Flight Center has stated that selection of the space station truss for assembly in space was based solely on economic factors. Even with the astronauts' combined training and flight costing $50,000/hr, the structural assembly time of the space station dual keel truss totals only $9 million (labor only). In contrast, projected developmental costs for automated truss builder machines far exceed

[73]Stanford Research Institute, *NASA Space Station Automation AI-Based Technology Review*, NASA Ames Contract NAS2-11864 (March 1985).

this figure--generally by a factor of 5.[74] This cost difference may not be so pronounced in the future, but for now, *cost-effectiveness* is the driving factor in selecting space structures assembly techniques. Combinations of EVA and automated machines may be considered in the near future as the most economical balance between lowered risk and EVA contingency capability.

Robotic Systems

NASA has developed several types of robotic systems that embody most of the current automation technology. There are also some semiautomated robots being developed that combine large computer and automated assembly line technologies. This discussion is limited to robotic systems designed for assembly or construction in space.

Assembly

The assembly type of construction implies that a beam or a truss structure is componentized, launched with the shuttle, and constructed in space. The EASE/ACCESS systems, which were assembled by hand, and the Delta Space Station concept were early predecessors of possible automated deployment mechanisms for supporting space-type assembly. The word "deployment," when used in NASA's context, generally implies automation and assembly procedures guided by some type of artificial intelligence or expert system.

As mentioned earlier, the cost of developing these systems is usually quite high. An example of a moderately sophisticated deployment system for a truss structure is that of the Delta Space Station. In this unique concept, components are stored within the shuttle bay and deployed automatically in orbit without EVA.[75]

Smaller deployment mechanisms consist of antenna masts made of fiberglass and deployed automatically by rotating drums. This concept is based on polymeric structural members' ability to bend.[76]

Beam Builder Machines

The concept of transporting a beam construction robot in the shuttle bay and deploying it in space is not a new one. As noted previously, Marshall Space Flight Center has developed an automated beam builder. The purpose of the beam builder is to assemble and spot-weld triangular truss structures while orbiting in space. The advantages of such a system are that, theoretically, it would be possible to ensure tolerances by transporting only sheet metal, folding it, and spot-welding it in space. The weight of the machine is minimal compared to that of the shuttle. The beam builder's potential success is based on an assembly concept using thin flexible structures. Test models at Marshall Space Flight Center have provided documentation on the stress and resiliency of the structures. However, the prototype machine has never been tested in a shuttle flight.

Another beam builder machine resulted from the energy crisis 10 years ago. At that time, NASA was studying large solar arrays and mirrors. These mirror assemblies--

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[74] Interview with G. Hall, Marshall Space Flight Center (June 1986).
[75] *Delta Space Station.*
[76] R. Schock.

some 20 mi in diameter--would focus solar energy on Earth-based receiving stations in an attempt to improve U.S. energy independence. Structural members for these assemblies were developed in a joint effort between McDonnell Douglas Astronautics and Johnson Space Center. The result was a proposed "wire-cage" geodetic beam, or cylinder, about 5 ft in diameter. This open-lattice cylinder was to consist of metal matrix composite materials and polymer composites.

The basic assumption was that one shuttle flight would carry enough material for 20 mi of beams. The beams would be fabricated automatically in space and assembled with special connectors by astronauts during EVA with maneuvering unit assistance. The beam builder was never constructed, and no other concept to date has proposed such large-scale structures and developed the construction technology as far.[77] The major problems with automated beam builders are quality control and final inspection in a vacuum environment. These problems, along with the extra weight of the machines on the shuttle, have hampered direct application of the technology. Future advances in this area may mitigate these concerns.

Remote Manipulator

The most familiar technology for robotic construction is the Remote Manipulator System (RMS) aboard the shuttle. The RMS has been used for all types of manipulations, including assembly of the ACCESS truss by an astronaut on flight STS-61B. The RMS is a six-degree-of-freedom robot arm with different end effectuators. In the EASE/ACCESS mission, the astronaut, with foot restraints, used the RMS to provide a base for manual rotation of the 45-ft-long truss. The RMS serves as the baseline for future development of a mobile robot arm system that will perform tasks associated with large masses or with high risks for EVA. At present, the space station RMS is not conceived to actually do construction during orbit, but that type of work could become an option later.[78]

Repair Systems

Repairs in space, some associated with construction, are a major concern and are mentioned in the ARAMIS study several times. One of the repair devices conceived for both servicing and repair work is the Orbital Maneuvering Vehicle (OMV). The OMV could be used for contingency events, emergencies, and high-risk activities.

MIT Space Systems Laboratory has been conducting underwater testing with a simulated OMV and some EASE/ACCESS prototype components to determine the feasibility of structural assembly in space using robotic systems. Because of gravity and orientation problems, other OMV tests at Johnson Space Center are highlighting the need for developmental work on positioning, torque application, and control systems.[79]

Although the OMV could be available for construction in addition to repair, most NASA personnel interviewed stressed the importance of trying this work first on Earth under controlled conditions if possible. Because the space environment is hostile, the

[77] T. Dunn, *Geodetic Beam Development Tests*, NASA Technical Memorandum 58271 (Johnson Space Center, January 1986).

[78] H. G. Taylor, "Large Scale Manipulator for Space Shuttle Payload Handling," *Teleoperated Robotics in Hostile Environments*, H. Martin and D. Kuban (Eds.) (Robotics International of SME, 1985).

[79] S. Walters, "Synergy in Space, Man-Robot Cooperation," *Mechanical Engineering* (January 1985).

added risk of using space-constructed items in fragile structures is not considered an appropriate approach. This concern also is associated with the shuttle-borne beam builder.

Control Dynamics of Structures

Structural Dynamics

As discussed in Chapter 3, the structural dynamics of a large assembled structure become unique in space due to weightlessness and susceptibility to vibration. Other components of structural dynamics in space include the relationship between the passive and active systems of vibration control and the artificial intelligence (i.e., robotic) systems used to control them. Immediate sensing of structural dynamics and feedback to motion sensors, momentum controllers, and other types of structurally responsive strengthening and stiffening systems in space can cause any flexible beam to become almost a live structure--robotic, in essence.

The process of sensing stresses at various points within a structure and translating them into actuator responses by using decremental forces is a science called "active control structural dynamics." One of the inherent requirements for structural components is low mass. Because of the low mass and typically thin sections, they also are flexible. As a flexible structure orbits in space, it can be stiffened automatically through the use of sensors and momentum controllers and actuators. The problem is that, for a geometrically very large structure, although its actual mass is very small, the mass of the structural dynamic controllers installed to stiffen it under vibration conditions becomes large relative to the mass of the trusses and struts in the structure. The mechanism used to control the structure for vibration and shock thus would be larger than the structure itself and the tradeoff for cost-effective deployment would become questionable.[22] The development of "live," intelligent structures is limited by this design conflict.

Motion Sensing

Because structural components in space are free-floating, motion sensing and the ability to retard or accelerate that motion on the component are a necessary part of the automation and exert additional forces on the structure. It is this active control that makes a thin, flexible beam or truss structure appear "alive" in a space environment under these conditions, control of position and attitude relative to the Earth (tracking, pointing), actuating of retrorockets mounted on the beam's structure to position, and negation of the bending stresses through control dynamics on the structure itself all interact to comprise several complex motion systems.

All of these forces, when integrated, create a very sophisticated mechanism from what would ordinarily seem to be a simple beam. The effects of positioning, atmospheric drag, and other forces would result in action-reaction type systems in which motion would have to be retarded. Therefore, in a weightless environment, in which all forces and reaction are contained within one entity (i.e., the beam structure), the control dynamics, motion sensing, and retardation all form a central complex. These control systems can become quite complicated mathematically. The actuators act like small

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[22] G. Doane, D. Tollison, and H. Waites, *Active Control of Large Space Structures*, NASA TM 86490 (Marshall Space Flight Center, February 1985).

control robots with artificial intelligence and expert system management. This type of control is considered possible, but is not fully researched at NASA centers.

Two types of motion sensors and actuators are being studied for their potential to arrest motion in flexural beams. These are (1) momentum devices called CMGs and (2) momentum actuators consisting of solenoid-type valves programmed to exert a counterforce at the precise moment when an original force is applied. The interaction and control mechanisms between these devices demand a high degree of sensing dynamics controls and artificial intelligence.

Robotic component control for space beam dynamics is under intense research at both Langley Space Center and Marshall Space Flight Center. A problem in simulating these mechanisms is the impossibility of modeling realistically the structural dynamics in zero-G on the Earth's surface due to gravity. Therefore, although models and computer simulations can be constructed, they are impossible to verify unless the structure is tested in a space environment. This issue is under study for all types of LSS.[81]

Sensing Intelligence

Sensing devices are based on the assumption that some system senses motion or flexural stress in a member and exerts a degree of evaluation and intelligence to counteract that motion, either intentionally or unintentionally. These flexural stresses may be caused by otherwise undamped vibrations. The expert systems and artificial intelligence for these counteracting components, in which a beam almost becomes a robot, are under development.

The sensing and control problems associated with large space structures are documented in a paper by Nurre, et al., dealing with structural dynamics, aerodynamics, and control.[82] A generic description of dynamic problems is covered in a paper by Ryan.[83] Sensing and control can be simulated on a computer using CONTOPS,[84] but with the same limitations as other methods (i.e., lack of zero-G verification).

Artificial Intelligence/Astronaut Interface

As mentioned earlier, future construction research may focus on some combination of astronaut labor and robotic systems. Contingency demonstrations on shuttle flights, such as satellite recovery, have shown that this interaction is feasible. Use of the robotic arm on the shuttle also has a demonstrated capability and could support construction operations for activities that are impossible for astronauts to handle due to the spacesuit gloves. Additional limitations of the spacesuit are that it is under high pressure, making it difficult for astronauts to bend their arms and close their fingers. Therefore, astronaut/robotic interfaces to assist in space construction are needed.[85] At present, R&D on these interfaces is at the research and prototypic stages--especially for use in space construction. The implications for other applications, however, are becoming evident and are discussed here to show the state of the art.

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[81] *Space Station Systems and Large Space Structures.*
[82] G. S. Nurre, et al.
[83] R. Ryan.
[84] *A Control System Simulation for Structures With a Tree Topology (CONTOPS).*
[85] *Analysis of Large Space Structures Assembly.*

Teleoperation

Teleoperation is the robotic, visual interface between the astronaut and the object he or she is trying to manipulate. In this case, television feedback is the only method that offers a sense of orientation and location of the object being manipulated or maneuvered into position. Teleoperation can involve automatic manipulation of large truss structures from inside the shuttle or from operations centers on Earth. Teleoperation has been used several times in vehicles sent to Mars and other planets and therefore is not a new technology. Teleoperation using robotic "hands" is now used in nuclear power plants and for handling radioactive materials through lead-impregnated glass walls.[86] Teleoperation in construction with artificial intelligence also has been used in rehabilitating handicapped persons; however, it has not been used specifically for space construction.

Telepresence

Telepresence involves feedback mechanisms in which pressure sensors and touch/feel sensors are combined with robotic techniques, including vision and pattern recognition, to give the operator a sense of "presence."[87] For instance, the operator console may have finger pads that press back to the operator's fingers with equal or proportionate force when their distant counterparts meet some degree of resistance to motion. This action gives the operator a sense of presence in the distant scenario being conducted, i.e., that he or she can actually "feel" the object being manipulated by remote control. This telepresence allows the operator to determine when the pressure is too great or when some other force may resist an anticipated movement. Telepresence is a new field with many potential applications for construction in space. Based on studies of astronaut cost-effectiveness, the development of telepresence could make astronaut labor more economical. NASA is conducting research in this area at Langley, Marshall, and Johnson Space Centers.

Sensing Feedback/Artificial Intelligence

In the operation of any telepresence-type device, the feedback mechanisms and sensors are primary components. These mechanisms must interface directly with some degree of artificial intelligence or expert systems. As the interface between the object (e.g., a large truss beam) and the astronaut becomes more sophisticated, it can also use higher levels of automation. For instance, pattern recognition used for orientation of end-effectuators is one case in which artificial intelligence may be necessary. The use of an expert system to maintain attitude control on large space antennas while they are being manipulated is another example.

The sensing feedback/artificial intelligence interface is under study within NASA and the robotics industry. The applications for construction in space are numerous, the most important of which are new types of sensing devices for structures and mechanisms for reducing the EVA risk to astronauts.

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[86] H. L. Martin and W. R. Hamel, "Joining Teleoperation With Robotics for Remote Manipulation in Hostile Environments," *Teleoperated Robotics* (Robotics International of SME, 1985).

[87] J. Wilson and D. MacDonald, "Telepresence--Goal or Byproduct of Remote Systems," *Proceedings of Robots 10* (Robotics International of SME, April 1986).

Cost-Effectiveness

In considering automation for construction in space, there is a clear relationship between the cost-effectiveness and risk factors. As the risk increases, the attempt to replace human labor with automation intensifies. However, a reduction in risk increases the cost of developing and employing intelligent machines.

Earlier studies on the space station showed that astronauts provide the most cost-effective assembly for this type of LSS. This is one application in which development of the joints and connectors along with the construction method offer a more economical solution than any type of automated beam structure assembly.

This situation may change in the future, in particular because of the 1986 Challenger disaster. Many more deployable structures may be launched because they require minimal astronaut interface and use more automation than do EVA-assembled structures. Also, the cost of sensing devices, etc., may become more reasonable as the technology is perfected, possibly making automation more cost-effective than astronauts in EVA.

The development of both commercial and military structures in space may be enhanced in the future by using automated assembly techniques. The R&D in this area is being conducted at NASA centers and universities, and in the robotics, automation, and expert systems industries. Application of this technology to construction in space is yet to be fully developed; areas for which further research is needed are identified in detail in the ARAMIS study[38] and in another report relating automation needs to future space station applications.[39]

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[38] D. Akin, et al.

[39] *Advancing Automation and Robotics Technology for the Space Station and the U.S. Economy*, NASA TM 87566 (Advanced Technology Advisory Committee, Johnson Space Center, April 1985).

5 THE EASE/ACCESS MISSION

Purpose

The EASE/ACCESS mission was designed to evaluate human productivity in space by determining (1) astronauts' ability to assemble large-scale structures and (2) the nature of training, preparation, and assembly sequences. It also focused on the hardware required for construction of large trusses in space.

In the literature dealing with construction of large antenna systems, there is a deficit of real flight-test information on items actually constructed in space. In fact, many publications contain only conceptual projections for structures. Some interviewees have commented that most construction in space has been done by "artists."

To date, EASE/ACCESS is the only construction-oriented experiment conducted in a space environment. As mentioned earlier, EASE/ACCESS was flown on space shuttle mission STS-61B, October 1985. The acronyms EASE and ACCESS stand for Experimental Assembly of Structures in EVA, and Assembly Concept for Construction of Erectable Space Structures, respectively. The mission was sponsored by NASA with responsibility divided between Langley Research Center (structural design of the ACCESS parts), and MIT Space Systems Laboratory (design and analysis of the EASE components).

The mission was successful in the sense that all original research objectives were achieved. It is important to realize that no other state-of-the-art construction research matches this unique experiment in terms of scope, depth, and success. Results of EASE/ACCESS were described at the Construction in Space Conference held at Langley during August 1986 (no proceedings available). Information presented at that conference is being considered in developing baseline conditions for a prototype space station.

In the experiment, a 45-ft-long beam was constructed using the ACCESS components and a 12-ft-long, six-member tetrahedral truss was assembled from EASE components. The beam and truss were constructed during two EVAs, each of which was carefully planned and monitored to determine the productivity and medical results and to maximize safety.

The productivity data collected will serve as a baseline for evaluating future task assignment and for designing cost-effective hardware that minimizes EVA tasks for space station construction.

EASE

The EASE mission consisted of assembling a tetrahedron designed by the Space Systems Laboratory at MIT. Twelve-foot members were used with simple clasp-type joint connectors at either end. Nodes for connection details were also used. The structure's exterior was coated with white paint and a polymer to prevent absorption of solar heat. The tetrahedron was assembled from components placed in a rack (the MPSS) and then demounted in the shuttle bay. Assembly was done during EVA to determine efficiency and productivity of astronaut movement. The entire exercise was videotaped to allow in-depth analysis of time and motion. Manipulation ease, positioning, clasp tightness and astronaut energy expenditure were included in the evaluation.

ACCESS

The ACCESS experiments consisted of assembling a 3-ft-long (edge) triangular truss to a length of 45 ft. This activity was designed to provide data on structural assembly tasks when astronauts are in foot restraints and can execute the assembly procedure on a rotatable assembly line fixture (Figure 13). Components were held in canisters and pulled out as required. The components were joined together to form individual units called "bays." As additional bays of the truss were assembled, the entire structure was pushed farther up on the fixture so that lower bays could be attached, and so on until the 45-ft "tower" was completed.

The tower was then removed from the fixture. Next, an astronaut positioned on the end of the remote manipulator system moved the truss tower using his physical strength to demonstrate the amount of energy expended in manipulating large structures in space. Finally, the astronauts disassembled the structure and restowed the components.

For both EASE and ACCESS, the assembly and disassembly of structural components were repeated six times during each EVA. Data were collected using camera tracking and metabolic rate measurements; however, there were no strain or deflection gauges on the structures for determining dynamic responses under weightlessness. Neither structural system was intended as a simulation baseline for the space station; human engineering was the main issue under study.

The data were analyzed at MIT to determine productivity, human muscle force, and ease of assembly for both types of components. Results are not yet in published form.

Materials

The EASE/ACCESS experiment used traditional aeronautical materials. All struts were made of machinable aluminum alloy. In the ACCESS experiment, because it was necessary to mitigate temperature differentials from one end of the strut to the other, the aluminum strut was covered with Kapton®, an aluminized polyimide film covered with a lithium nitride layer to simulate a gold, reflective surface.* The astronauts indicated no sense of temperature differential through their suit gloves for any of the struts in either experiment.** The materials used for the joint connectors and for movable components of the strut assembly also were made of common machinable aluminum alloy.

Mission Planning

Payload Management

The documentation described at the Space Construction Conference underscored the amount of preplanning required to determine payload configuration in the shuttle bay, distribution, high G-forces on the devices holding structural components during launch, and structural component effect on the shuttle's center of gravity.

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*Kapton is a registered trademark of E. I. duPont de Nemours, Inc.

**Interview with LTC Jerry Ross, astronaut on space shuttle mission STS-61B (7 August 1986).

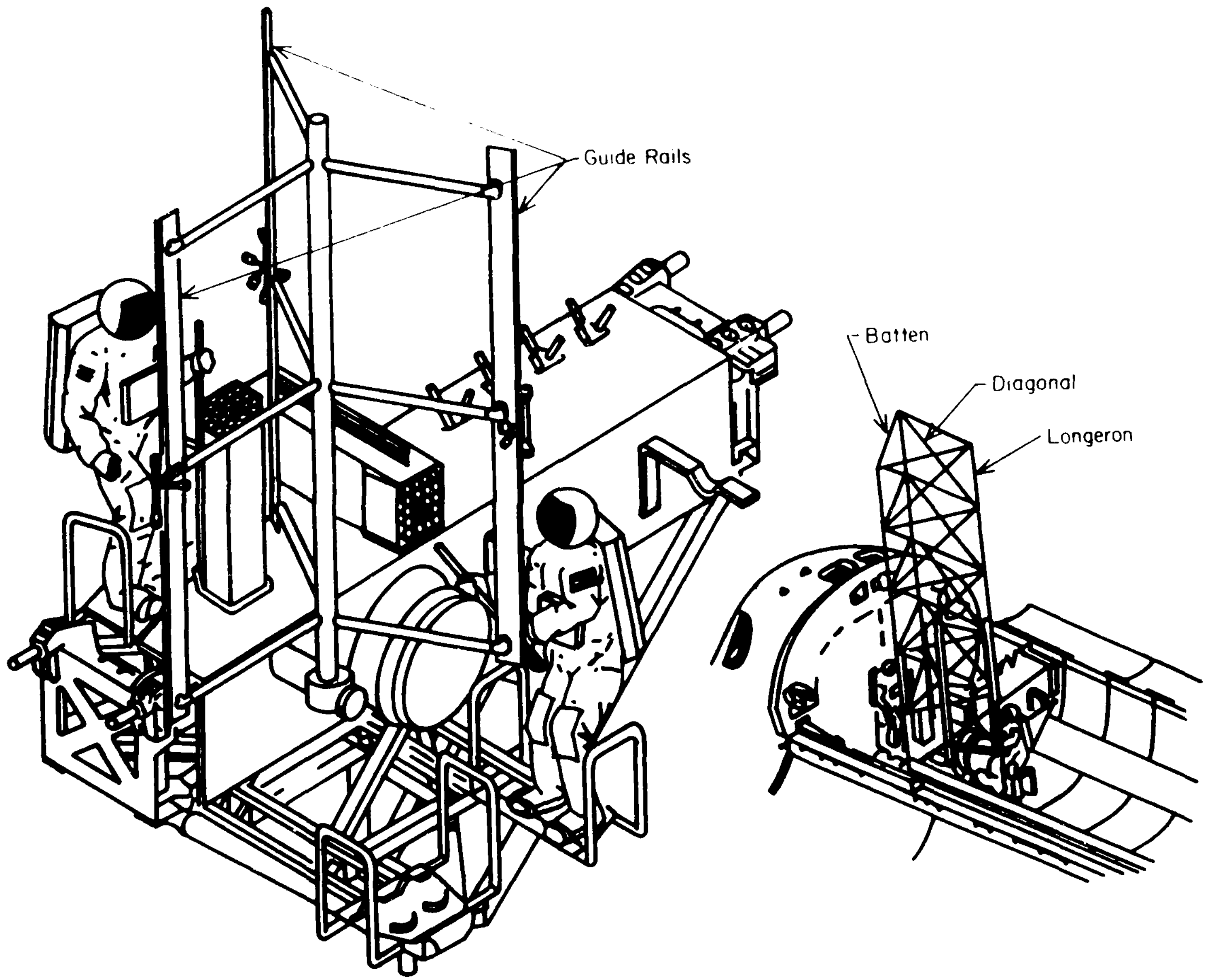

Figure 13. ACCESS: astronaut EVA assembly procedure.

Payload integration, preparation, testing, and evaluation are complex processes in which NASA attempts to ensure the safety of the cargo and crew by arranging the payload in the best possible way. Much of the mission planning for the structures assembly experiment was far more involved than what would be expected for a simple structures task. However, good payload management had an important role in the successful, productive execution of the EASE/ACCESS mission.

Clearly, the payload configuration would be a major consideration in preplanning a major construction project in space. The cost of this task, combined with that for astronaut labor during assembly, can easily be ten times the total amount spent in design and manufacture of a system. However, because of the tremendous cost of each mission and the mandatory safety requirements, it would be very difficult to reduce efforts in payload preplanning.

A worthwhile observation is that the requirements for mission planning are so extensive and detailed, and performed so carefully, that substantial benefits could accrue by standardizing components and mission plans before structural assemblies are sent into space. As with military construction on Earth, standardization could dramatically reduce project costs. For example, structural components, procedures, safety checks, and all other elements of NASA's flight preparation would have to be specified only once and these specifications would be used over and over again. In particular, trusses are a good candidate for standardized planning because of their repetitive design. The Air Force is seeking innovative standardization methods for reducing the cost of future missions.

Space Certification of EASE/ACCESS

Certification of structural members for space flight in the shuttle has a number of meanings. It implies that all materials to be flown in the shuttle have been evaluated prior to launch in terms of structural stability in the shuttle during launch. It also means that components have been evaluated for long-term durability under radiation exposure and have been approved by both NASA Mission Planning and the astronauts who will work with them in space. Because of the large number of personnel with diverse responsibilities involved in the space certification process, it is very expensive and time-consuming.

NASA has developed a sequential procedure for acquiring space certification of the EASE/ACCESS construction elements. A contractor could potentially save overall construction costs by studying this procedure, as it was used for EASE/ACCESS, before submitting materials or even before designing structural components. Space certification involves a wide array of steps ranging from determination of vibration and dynamic loads on structural assemblies in the shuttle bay to assessing the impact of the cargo's rough or abrasive fittings on spacesuit glove wear. The structures designed for space construction must meet all constraints and conditions of this process.

Training

In preparing for the EASE/ACCESS mission, a great deal of training and simulation were required before final approvals were given. Most of the training was conducted in underwater tanks at Marshall Space Flight Center or Johnson Space Center. Analysis of the EASE/ACCESS mission flight data showed that effort expended in neutral buoyancy tanks is a relatively good predictor of the amount of time and effort required on space assembly missions. Much of these data have been verified by results of MIT's analysis of the videotapes.[91]

The assembly procedures for actual structures in space would require careful development of the sequence of EVA operations down to identifying where handholds will be placed and how long the astronauts will remain in certain positions to minimize fatigue.

The training required for mission planning is quite expensive and usually must be started 6 to 9 months before the mission begins. The care, preparation, and sequencing of all training components are done very carefully. A critical element of mission training is determining the number of contingency plans needed in case something goes wrong. Contingency planning can take up an estimated 30 percent of training time but is considered to be worth the investment.[92]

Based on the EASE/ACCESS experience, the assembly of structures in space appears feasible, cost-effective, and within the range of astronaut physical abilities. The experiment also indicated that training in neutral buoyancy tanks is a reasonable predictor of mission element times for EVA. During an interview, LTC Ross said that he found the construction of structures in space during EVA to be easier than that of the same structure in the neutral buoyancy tank.

Human Workers in Space

Metabolic Rates

Earlier research by NASA has focused on predicting how humans would handle living and working in a space environment.[93] Part of the purpose of the EASE/ACCESS mission was to determine, through data analysis by MIT Space Systems Laboratory, the effect of EVA tasks on metabolic rates of humans in spacesuits and how various parts of the human body are involved in and affected by the effort expended during assembly tasks. Studying metabolism is logical because of the tremendous cost of EVA and the potential effects of fatigue on productivity.

An important element in evaluating metabolic rate is the amount of energy the astronaut uses to maintain an effective stable position for the lower body. Results of the EASE/ACCESS mission as presented at the Space Construction Conference by Dr. Horrigan of Johnson Space Center suggested that only 25 to 30 percent of the energy expended could be attributed to manipulation of truss components.[94] A larger amount of metabolic energy was used in keeping the lower body in place or manipulating the total lower body mass with the arms. In particular, this energy expenditure is fatiguing when an astronaut must manipulate large free-floating beam members such as those being

[91] D. Aiken, et al., "Neutral Buoyance Evaluation of Technologies for Space Station External Operations," *International Astronautical Federation Congress* (October 1984).

[92] K. Havens, "Synopsis of EVA Training Conducted on EASE/ACCESS for STS-61B," presented at the Space Construction Conference (August 1986).

[93] W. D. Compton and C. Benson, *Living and Working in Space: History of Skylab*, NASA-SP (1983); M. Connors, A. Harrison, and F. Akins, *Living Aloft: Human Requirements for Extended Spaceflight*, NASA SP-483 (1985).

[94] J. Horrigan and J. Waligora, "EASE/ACCESS EVA's: Biomedical Data," presented at the Space Construction Conference (August 1986).

considered for the space station. In a more recent projection for space station assembly tasks, astronauts would be confined in the shuttle bay with foot restraints and would move into different positions with the help of a robotic arm or tracking elevators. The SAVE experiment described later in this chapter provides more details. The goal is to find ways of keeping metabolic rates reasonable and reducing fatigue.

Metabolic rate and energy expended also are related to the air pressure inside the spacesuit, which is 4.7 psi, and the amount of effort required to manipulate the gloves to grasp objects and to move the arms. Glove technology was mentioned as a constant problem in terms of sensing and manipulation. It should be noted that many of the space station truss structural design joint parameters are dictated by glove capability and hand-muscle effort and access. Other factors related to the spacesuit are described below under *Suit Interface With Construction Tasks.*

Fatigue

Since the total effort to construct the space station could involve all mission specialists on an estimated 20 to 30 shuttle flights, fatigue in relation to productivity could become a major issue. Astronauts for the EVA/ACCESS experiment said fatigue during EVA assembly in space was affected by three major factors:

1. Lack of Foot Restraint. Because the assembly of large truss elements requires the astronaut to free-float in space, energy is expended in moving three separate masses: the tethered beam, the new beam to be attached, and the human body mass. The upper arm stress and muscle energy expenditure are quite high for this effort. Better preplanning for location of foot restraints would have allowed the lower body to contribute to leverage for moving the various elements. Foot restraint positioning must be integrated with the structural design, assembly, and joint details.

2. Task Planning. Much of the task planning before the flight consisted of analyzing hand and body motions in neutral buoyancy tanks to optimize positioning and holding of construction elements until they were ready for assembly. The astronauts believed their productivity was much higher than it would have been without this experience. Assembly of the ACCESS triangular truss was facilitated by the mounting fixture that later became part of the structure. Thus, careful design of assembly fixtures for the shuttle cargo bay improves the overall productivity of EVA, thereby cutting mission costs and making construction activity safer.

3. Manipulation Ease. Astronauts used very little effort in manipulating the ACCESS truss in space. Movement of the 45-ft truss required almost "finger strength" to push it into a rotational mode and to bring it back to a stable position. The major problem with manipulation was in making sure the astronaut had a footing base (see paragraph 1 above) and that the person operating the RMS was tracking the arm's location and activity occurring at the end of it. (There are blind spots in operating the RMS due to window configuration and operator depth perception.[95])

LTC Jerry Ross also noted that fatigue is related to many other factors, including expansion of the human spine during weightlessness.

[95]Interview with Dr. M. Cleave, Space Construction Conference (August 1986).

Mission Duration

LTC Ross indicated that mission duration of approximately 6 hr for EVA was about right to minimize fatigue and maintain productivity. He also suggested that mission planning provide for EVA work every other day. In terms of construction scheduling, this implies having four mission specialists prepared for alternate days of construction. Further analysis of the EASE/ACCESS data may reveal more effective productivity planning for construction missions along with baseline constraints.

Suit Interface With Construction Tasks

The spacesuit is a large machine that provides the astronaut with an environment in which to live; however, it restricts physical movement. Previous suits have interfered with the ability to bend arms, and gloves create problems with manipulation. Since the astronaut's ability to grasp objects for all types of tasks is very important, the present glove is being redesigned.

Analysis of suit components and foot restraint methods could reveal methods of reducing human energy usage and thereby reduce fatigue. Several biomedical concerns are being addressed continuously in a program for improving spacesuits. These issues are mentioned here because suit design and EVA tasks are directly related to the types of construction tasks that can be done in space.

At present, NASA is considering developing a machined aluminum hardsuit with ball-bearing joints for use in space station construction. In terms of extra safety and protection for the tasks anticipated, this design would be a major improvement over the present synthetic fabric suit. Air pressures in the suit and in the final space station have not been determined. Lower-than-atmospheric air pressures require that astronauts prebreathe pure oxygen to reduce the danger of developing the bends. This process can take up to 3 hr before and 1 hr after each EVA. This issue will be resolved during the preparation of the final space station baseline.[96] The EASE/ACCESS mission has pointed out the need for consideration of human biomedical performance issues in construction mission planning.[97]

Automation for an EASE/ACCESS-Type Mission

Near-Term Potential

It appears that much of the preliminary testing and evaluation for space station structural components, assembly techniques, and joint design will use a combination of EASE and ACCESS EVA approaches. However, other ongoing research at Langley and Johnson Space Centers is seeking robotic applications for automated manipulator arms to connect structural joints together in space.

The RMS applications also are derived from the structural assembly techniques developed for the EASE/ACCESS mission. Both laboratories have demonstrated that it is feasible to use end-effectuators to rotate and latch member joints for space structural connections using the EASE/ACCESS systems. However, inspection and verification of

[96]Interview with Mr. Mark Cohen, Space Systems Architecture Group, Ames Research Center (November 1986).
[97]*EASE/ACCESS: Post-Mission Management Report.*

correct connection is much more difficult under these conditions because the artificial vision technology lacks refinement. Additional research related to teleoperation and telepresence is underway at some universities and other NASA centers.

For the near term, it is the astronauts' opinion that state-of-the-art automation cannot nearly provide the flexibility that the astronaut can nor the payback for the investment dollar. Although assembly procedures have been demonstrated with Earth-bound robots, there are several problems with maintaining robot orientation stability in space as the assembly task proceeds. An example is MIT's underwater robot beam assembly experiment being conducted at Johnson Space Center.[98] The underwater robot must grasp onto an adjacent beam to position itself correctly and to provide a firm foundation for positioning the new beam into the joint connector.

Again, automation for space construction has seen limited R&D at this point, but has much development potential. NASA's prevailing attitude, because of the target date (1993) for creating the space station, logically emphasizes development of astronaut-assembled, erectable trusses. However, the high cost of shuttle flights may eventually shift emphasis to partially deployable structures like those in the Delta Space Station proposal from JSC, or a combination of approaches may be used.

Far-Term Projections

At the Space Construction Conference, one speaker noted that far-term applications for automated space construction are just that--far-term. It is assumed that automation technology will continue advancing, but for the near term, most of the R&D in construction applications will focus on erectable trusses as discussed above.[99]

A corollary to this observation is that at present, there is a great deal of discussion about combining the shuttle with manned assembly support for erectable truss components and also using other rockets for deployable or semideployable trusses to be launched into space and then further deployed by astronauts. However, NASA is focusing on erectable structures because of the need to move the space station program along, as also discussed above. In the far term, NASA will continue to support automation for space construction technologies ranging from automated tooling to manipulator system robots that move along the flat faces of the space station truss.[100]

Developmental Needs in Automation

The EASE/ACCESS experiment and subsequent analyses have helped identify specific gaps in automation technology. It is proposed that future research for automated construction in space emphasize the following areas:

1. The automation and robotic assembly technique must build upon pretested, EASE/ACCESS-type hardware at first, with later emphasis on developing standardized space construction hardware and methods that are adaptable to robotic and EVA assembly.

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[98] W. Howard, et al., *Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Trusses*, NASA TP-2108 (March 1983).

[99] Interview with Dr. M. Mikulas.

[100] *Spacestation Reference Configuration Description*, JSC-19989 (Systems Engineering and Integration, Space Station Program Office, Johnson Space Center, August 1984).

2. The automation must develop algorithms and artificial intelligence to support construction contingencies in space. It appears that the technology required to determine what might go wrong and to preplan by developing contingencies is far beyond the capability of any existing artificial intelligence system.

3. Automation for space construction is limited due to problems with tolerances in quality control for manufacture in space. Thus, automation applications perhaps should be limited to assembly, rather than manufacture, of beams in space.

4. Automation for space construction must interface with humans. The most cost-effective mixture of automation and human expertise will be the final choice for assembly and construction tasks in space.[101]

The SAVE Proposal

EASE/ACCESS/SAVE

The success of the EASE/ACCESS mission has generated a great deal of interest for this type of construction activity in space. At the same time, there is pressure on NASA to provide a baseline evaluation of the proposed space station truss configuration and structural characteristics. Therefore, NASA has proposed the Structures Assembly Verification Experiment (SAVE).

SAVE will involve EVA construction of approximately 14 bays of the 15-ft truss proposed for use in the space station. Construction of the 200-ft long truss is expected to serve as a baseline structural test for several instrumented structural dynamic evaluations; in addition, it should provide data on astronaut productivity for assembly tasks on a large scale. This experiment is a major undertaking, but is necessary in view of the lack of actual flown, tested, and evaluated hardware for the space station. NASA is considering SAVE as a potential candidate for serving as a basic evaluation technology in developing the space station.[102] The SAVE structure will be instrumental for verification of Earth-bound structural mathematical simulations.

The Control of Flexible Structures (COFS) experiment is related to SAVE. However, COFS[103] will involve composite flexible structures with loose joints which are characteristically deployable (e.g., as antennas) in contrast to the SAVE mission which will use an erectable structure (Figure 14). The data from both experiments will be evaluated before the prototype space station is assembled and will serve as baseline configurations for the two structures (NASA has distributed the *Space Station Baseline RFP* for industry comments).

Space Station

The R&D for construction of the EASE/ACCESS structures will serve as baseline experimental data for SAVE. The SAVE mission is primarily for scaling up the various

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[101] D. Stuart, *Systems Analysis of Humans and Machines in Space Activities*, Ph.D. Thesis (MIT, April 1986).

[102] M. Mikulas, "SAVE," presented at the Space Construction Conference (August 1986).

[103] H. Bohon, "Control of Flexible Structures (COFS)," proceedings of the OAST Research Technology and Engineering Workshop, *Space Structures: Dynamics and Control*, Vol 2 (October 1985).

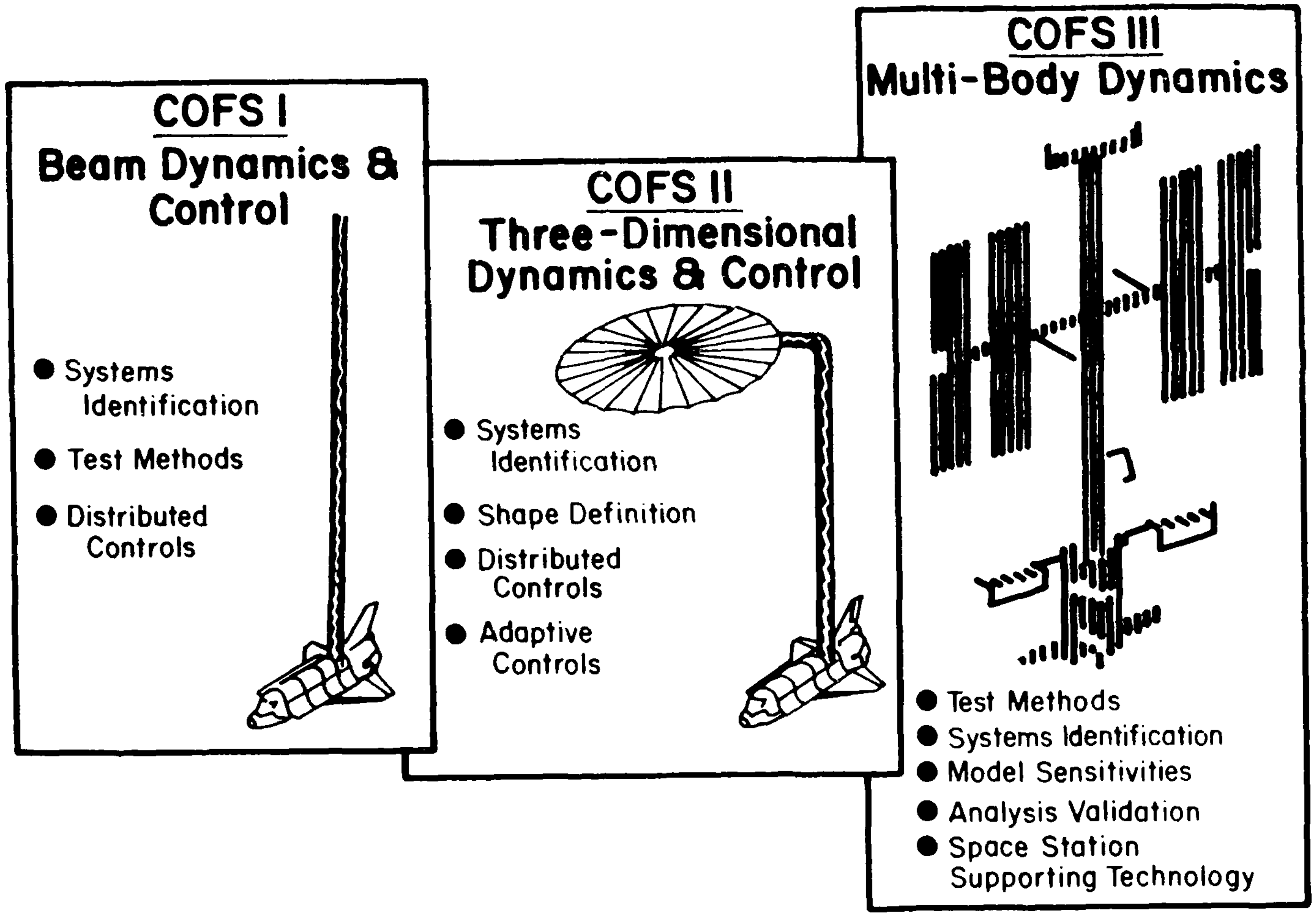

Figure 14. Control of Flexible Structures (COFS) concept.

mission elements to space station size and for verifying mathematical simulations. SAVE will then serve as the structural dynamics evaluation baseline for many of the simulation parameters and unknowns in construction of the space station.

It is evident that this R&D effort has a sense of management direction, control, and evaluation. The momentum generated by the success of the STS-61B mission, the success of the structural components, and the astronauts' construction abilities in low-Earth orbit all indicate that pretested, certified hardware developed using these two approaches will probably be the final choice for prototype space station construction.

NASA has a direct, clear mission in the space station objective. The success of the initial structural experiments and the continuous buildup of experimental and construction-verified data for assembly techniques suggest that the technology for erectable assembly of large structures in space is beginning to take form; nevertheless, much groundwork remains to be done before the space station becomes a reality.

6 HABITABILITY AND CONSTRUCTION IN SPACE

The technology for construction in space must address biological and physiological parameters of human performance. Space is a very dangerous environment; therefore, all human activity must be planned through a very careful evaluation of the opportunities and safety factors involved in achieving a balance that is cost-effective, yet maintains adequate productivity.

One parameter that must be evaluated is the harmful effects of radiation due to solar flares when astronauts are on EVA. The Van Allen belt of intense ionizing particles protects the Earth's surface from much of the harmful cosmic radiation. However, if the space station is built near this belt and if future expeditions are made to the moon, the requirements for protective shielding will increase dramatically. As an example, NASA had indicated that using aluminum materials for protective shelter on the surface would require almost 6 ft of additional lunar regolith material to provide adequate protection from radiation and solar flares.[124] Micrometeor impact is also a materials-habitability consideration in long-duration missions.

Another consideration for life safety is that, in a weightless environment, dust particles and small debris floating through the air are dangerous to human respiration. Therefore, the space station will need a means of filtering these particles and monitoring the concentration. Additional dust caused by materials processing and construction activities also is a major problem; dust generated during the construction process could be lethal.

Other habitability constraints in space related to materials applications include the difficulty of working with tools outside in a vacuum; communication; and security of materials used in spacesuits. These factors, along with human constraints and requirements, need to be identified in order to protect astronauts working in space. The habitability issue needs much R&D before construction in space can become commonplace. Integration of humans/machines/construction in the space environment is a requirement permeating all of the technologies covered in this report.

Space Station Staging

Module Design

The design of the proposed U.S. space station habitability modules, which are represented in conceptual diagrams as long cylinders attached to the space station (Figure 15), would impact construction activity for the space station and other structures.[125] Thus, the basic principles used in designing these modules have wide application for the generic-type construction activities that would occur in space. Among the basic principles are those dealing with (1) the design of connections between longitudinal modules and (2) the astronauts' ability to assemble space station modules in orbit. It is assumed that astronauts will be able to adjust and control large masses to create very fine mechanical interfaces with airtight connections. Much of the

[124] Interview with Dr. M. Avener, Life Sciences Section, NASA Headquarters (March 1986).

[125] *Space Station Architectural Elements Model Study*, NASA Contractor Report 4027 (Ames Research Center, July 1986).

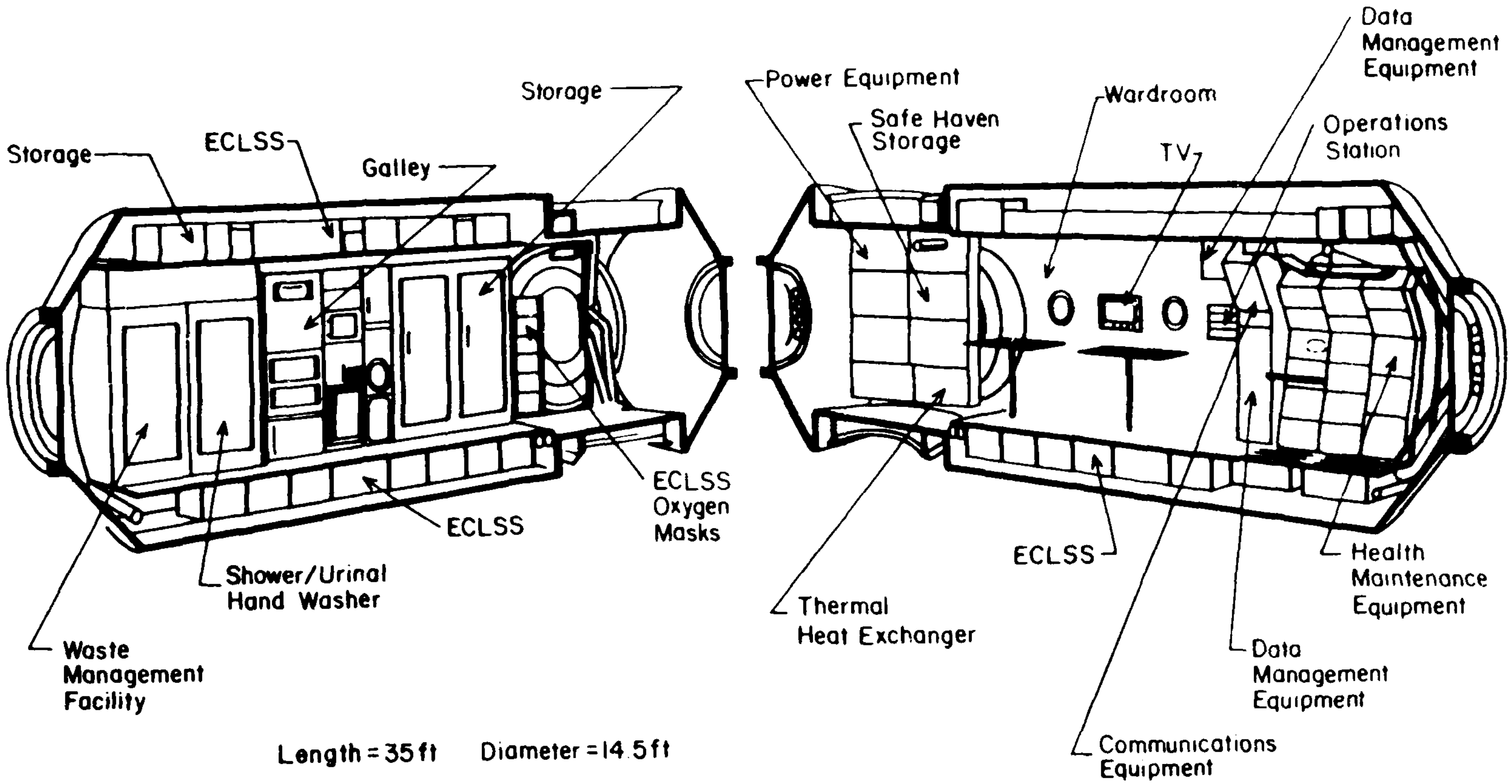

Figure 15. Interior of prototype habitability module.

astronaut's ability to control and manipulate this interface and adjust the station module into final position is not yet possible in a realistic construction scenario.

Ames Research Center has done several architectural modeling studies on the configuration of individual modules and their connection details. This research has resulted in a patent for habitability module connectors and also in the development of alternative configurations for connection structures.[106]

Modules that interface between various habitability workstations and sleeping quarters are outside the scope of this work. This report focuses on the construction activity impact on module design. In addition to the astronauts' physical constraints, the construction work itself is a concern and includes the need for spare tools, spare parts, repairs, and equipment maintenance. In other words, it is plausible that construction activity in space will require a workshop-type platform arrangement. Much of NASA's planning has assumed that all parts and pieces will be finely machined and manufactured on Earth and will fit together exactly. Although NASA has worked to improve part design and manufacture to the point where this condition may occur 99 percent of the time, it is also true that there is heavy reliance on the astronauts' ability to "jury rig" a solution in space.

As construction in space grows into a continuous activity, the need for a workshop module to support this activity will become established. Bringing a simple repair job back to Earth for servicing would be costly and labor-intensive. A workshop attached to the space station probably would be more cost-effective. NASA apparently has not studied this aspect in detail. Overall, construction scheduling and management probably have received inadequate emphasis in construction technology R&D.

EVA Sequencing

EVA in space involves a sequence of events carried out on a finely tuned schedule. During training, this activity sequence is carefully programmed among the astronauts who will participate in the assembly task. As evident from the EASE/ACCESS mission, all construction activity for EVA is planned with a very high level of detail.[107]

For the space station, this concept will need to be expanded to allow for habitability factors. Astronauts may need to plan their own alternative activities during the construction sequence, so that variations within the sequence must be anticipated. It is noted that most construction tasks in the EASE/ACCESS mission comprised experiments for which failure to assemble a certain structural member would not jeopardize the entire shuttle mission. It would have been possible to simply pack up the parts and go home, should the mission fail. However, in planning for space station construction, every effort must be taken to ensure the astronauts' successful completion of assembly because of the heavy financial commitment.

Therefore, astronauts must receive training for construction activity programming and contingency planning for EVA sequencing/redesigning tasks. Some construction planning experience was gained on the EASE/ACCESS mission, but extensive interface

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[106]Interview with Mr. Mark Cohen.

[107]K. A. Havens, "EVA Prep," presented at the Space Construction Conference (August 1986).

with ground station and ground control in Houston will still be necessary, with technical specialists aiding the astronauts during construction.[108]

Performance Issues

This report has noted several times that astronaut performance during short-term missions has been acceptable and tasks were completed within the given timeframes. However, on long-term missions for which construction productivity and performance would have comparable importance, it will be essential to identify all parameters that could affect performance and, thus, cost over the mission life.

In 1982, NASA contracted McDonnell Douglas to identify human-machine interfaces in order to improve productivity by developing tradeoff issues for tasks to be done by humans versus those which perhaps should be automated. The report[109] contains a series of tradeoffs to determine which tasks, including those related to construction, should be automated. However, the construction issue was not addressed in great depth and a large amount of research still needs to be devoted to this area. Nevertheless, the report's methodology could be applied to the larger issue of allocating resources for LSS construction.

MIT has compared underwater structural assembly performance with the human ability to construct items in space.[110] In addition, one of the main purposes of the EASE/ACCESS mission was to identify potential factors that would affect human productivity over long-term missions. However, data from both sources is for short timeframes. In contrast, the space station will be in orbit for a long time and crews will be sequenced rather slowly, spending from 90 to 120 days in space. Thus, productivity issues that may be inconsequential to short missions could become paramount to long orbits.

Lockheed Aerospace recently provided NASA with a report covering a wide range of productivity issues for humans in space.[111] Much of this report addresses the long-term factors that could affect human performance in orbit. For example, certain habitability parameters that are not considered necessary on a short, 7-day mission may become critical on a 6-month mission. The productivity issues range from architectural esthetics, habitability, crew compartment design, and sleep, to group dynamics and social interactions. This research, which is still in progress, is providing valuable data on productivity and cost-effectiveness of astronauts in space. The specific issue of construction productivity is not discussed separately in the report; thus, research should be done in this area to further strengthen the cost-effectiveness rationale. In general, the report is a unique, important document addressing long-term productivity--a major consideration in space station planning.

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[108] K. Havens; *Flight Data File, Crew Activity Plan*, STS, 51L-JSC (1985).

[109] *Human Role in Space*, NASA Contractor Report NAS835611 (September 1984).

[110] D. Aiken, et al., "Neutral Buoyancy Evaluation of Technologies for Space Station External Operations."

[111] *Space Station Human Productivity Study*, NASA Contract NAS917272, DR SE-10937 (November 1985).

Suit Technology

Suit Design

Effective performance of tasks requiring EVA for construction in space will be highly dependent on the efficiency of astronaut spacesuit design. On previous flights, astronauts have worn a well designed soft suit made of several layers of canvas fabric and rubber, and providing a 4.7 psi environment for work.

Now NASA is considering the AX-5 hard suit for the space station baseline standard.[112] This hard suit is made of machined aluminum with ball bearing joints that are geometrically designed to accommodate all normal human arm and leg motions. The suit has numerous positive features that make it promising for wear during construction in space. First, it is reusable. Second, it is easy to put on and take off, and is fairly easy to service. Furthermore, the suit's hard aluminum shell protects the astronaut to a moderate degree against cosmic rays and micrometeorite impact. The suit is still under consideration because cost is about 20 percent greater per life cycle compared with that of the soft spacesuit.

EVA Preparation Facility

Because the astronauts must check and verify their equipment before they leave the shuttle (or the space station), a specific time slot and physical space must be allotted for this activity. This preparation can become quite long because of the astronauts' need to prebreathe pure oxygen for 3 hr before EVA begins. Prebreathing is necessary to avoid the bends and other harmful effects of low-air-pressure environments. To construct the space station, an estimated 2000 tc 4000 hr of continuous EVA activity per year would be required.[113] Thus, a crew suit preparation area would be needed.

A prototype suit preparation area has been described, with some alternative configurations identified.[114] Although intended for the space station maintenance operations, this EVA preparation facility also could support requirements for construction in space. The EVA prep area will be almost autonomous (perhaps located inside the shuttle) and will allow continual shiftwork in constructing large structures. Crew support for suit maintenance and replenishment of consumables in the suit must be taken into account. The EVA prep facility is discussed further in another document.[115]

Tools Technology

The spacesuit to be worn during EVA construction is still under discussion, with several issues unresolved within NASA. The question of whether to use the hard suit has been discussed. The second issue deals with development of hand-manipulated end-effectuators or grippers for the hard suit. These tools supposedly would be inserted into the arms of the hard suit and operated manually from the inside; or, they could be a combination of human-robot interface. Another area under consideration is whether to

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[112] M. Cohen, *Human Factors in Space Station Architecture*, NASA TM 86856 (September 1985).

[113] Interview with Mr. Mark Cohen.

[114] M. Cohen, *EVA Access Facility: Presentation to Space Station Advanced Development Review* (Ames Research Center, October 1986).

[115] *Outfitted Habitability Module Assembly*, Space Station Work Package 2 (NASA, June 1986).

design a completely new type of glove for astronauts. The integration of these technologies could improve long-term productivity for construction.

The development of tools for construction in space is an area needing a great deal of research. The astronauts' productivity and the ability to assemble, check, tighten, and maintain various structures during activities in space are only as cost-effective as the tools permit (Figure 16). Because of zero gravity and the laws of motion in a weightless environment, applying certain torques to mechanical devices is very difficult, yet extremely important. All types of tools need to be developed in coordination with the structural design, construction procedures, and suit technology.

Medical Aspects

Heart Rate[116]

The astronauts' heart rates were monitored on the EASE/ACCESS mission to obtain a baseline for metabolism and energy expenditures during EVA construction. Oxygen consumption was also monitored and later correlated with the individual tasks. The energy expenditures were calculated based on kilograms of body weight. The measurement was unique in that the EVA tasks recorded on videotape could be correlated with energy expenditure. This analysis will provide important data for planning the SAVE mission in which a 15-ft-long truss structure will be assembled.

Radiation Exposure[117]

The EVA data collected during the EASE/ACCESS mission did not include radiation exposure. However, the 2000 to 3000 hr/yr of EVA planned for the space station will require that exposure parameters be evaluated.[118] The aluminum hard suit AX-5 may be used in determining the station baseline.[119]

Bone Loss and Spinal Expansion[120]

It has been known for some time that, during space missions lasting more than 7 days, there is a noticeable loss of bone from the human skeleton. The combined effects of physical exertion for assembling large structures during EVA and bone loss, if any, have not been investigated.

In previous missions, the astronauts' spines expanded as much as a full inch under weightlessness for a week. This condition did not hamper activity nor were there any serious after effects from the EASE/ACCESS mission; however, extended EVA times for assembling the space station truss could cause a physical problem due to spinal expansion.

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[116]*Outfitted Habitability Module Assembly.*
[117]*Small Business Innovation Research Document.*
[118]Interview with Mr. M. Cohen.
[119]*Small Business Innovation Research Document.*
[120]D. Horrigan and J. Waligora.

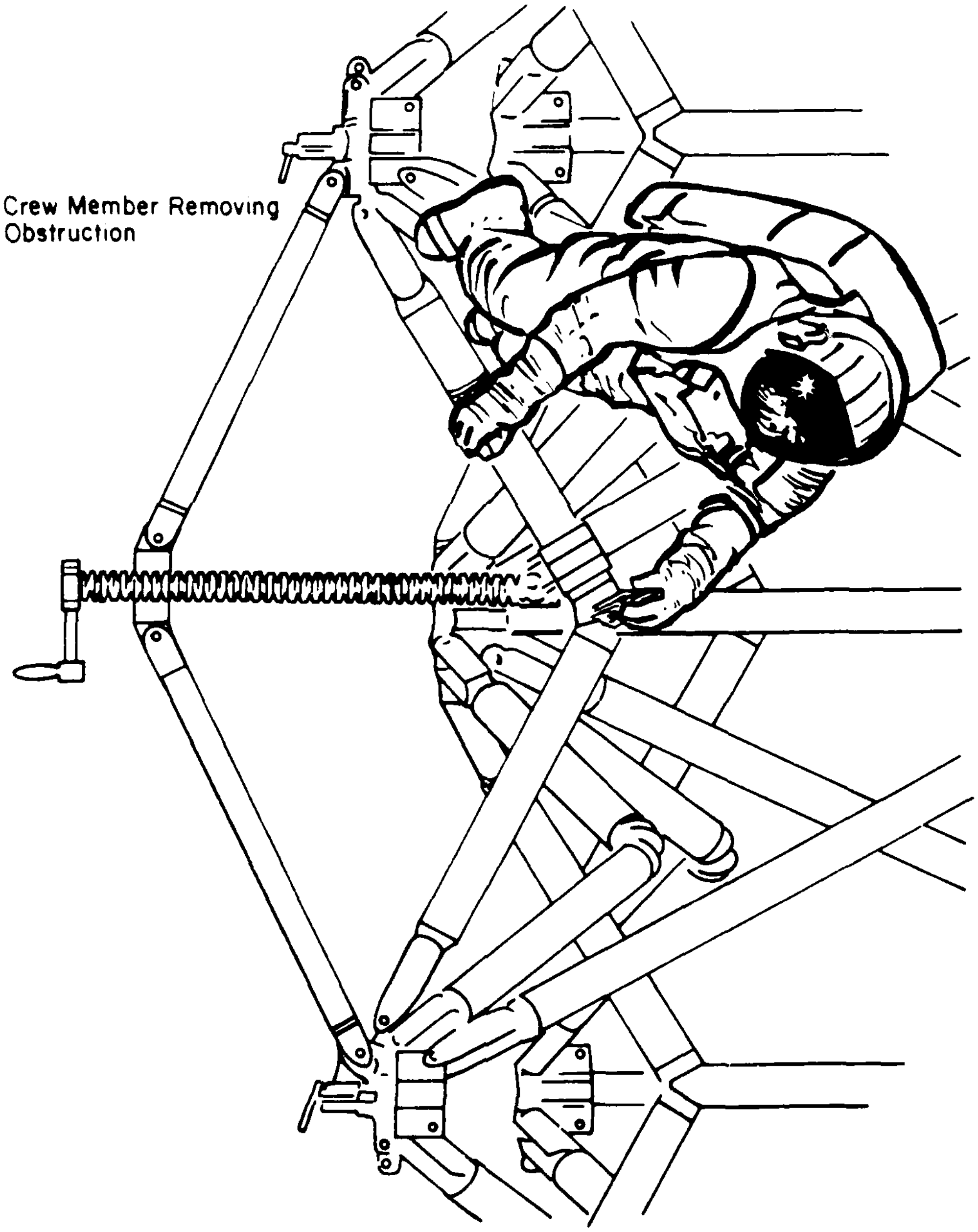

Figure 16. Tools: on-orbit use of structures jack.

Psychological Factors

Human psychological factors for construction in space have an impact on astronaut performance in that, if the total surrounding environment is not designed for the most cost-effective, efficient application of physical abilities, assembly time and costs will increase. Operation of the station and the individual tasks associated with it require special design considerations due to the long-term occupancy. NASA is studying these design factors in terms of sequential task analysis. A proposed module architecture has been described and psychological factors have been assessed with a new level of concern.[21]

Construction Management

Construction management as a specific cost issue probably is the most important nonpurchased component of a project. In case of the space station and other structures built in low-Earth orbit, NASA so far has given little consideration to this issue. However, it should be recognized that construction management has taken on a low priority because of the need to address more immediate concerns.

Management planning will need to consider the same type of situations found in construction on Earth, only in the context of the unique space environment. For example, in every contract assembly task, there is usually a need for an inventory and staging area, perhaps even a staging platform. The platform for construction in space is now considered to be the shuttle. Construction of the 15-ft box truss for the space station will likely use the shuttle bay architecture as the assembly component. This staging area is required for astronaut safety and for providing stability during assembly.

System Sequencing

Planning for assembly of large structures in space probably could benefit from a critical path method (CPM) system approach to sequencing construction activities. At present, there is no evidence that CPM systems used in managing construction on Earth have been applied to the sequencing of assembly tasks in space.

NASA's focus for assembly tasks has been on astronaut safety and on developing conservative approaches to various maintenance tasks. However, as the tasks become larger--for instance, assembly of a 400-ft-long truss--the sequence of activities, placement of inventory, and location of tools will be increasingly critical. Methods of fault detection, accident handling, and other safety factors also are major issues to consider for input.

Crew Monitoring

As in any construction project, it will be important to monitor the crew's productivity level, safety, and activity sequencing during space station assembly. Crew safety during the construction experiments was not analyzed in depth, although preplanning for the EASE/ACCESS mission included an extensive review of various safety aspects. Emphasis has been on overall operational safety.

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[21] J. Pitts, *The Human Factor, Biomedicine in the Manned Space Program*, NASA SP-4213 (1985); M. Cohen, *Human Factors in Space Station Architecture I.*

The technology for monitoring a crew during construction is not well developed.[122] The crew for the EASE/ACCESS mission was monitored through communication with ground control in Houston and visual observation. Technical experts aided the astronauts in assembling certain parts of the EASE/ACCESS structure. This same type of crew monitoring and coordination, with many variations, probably will be necessary for mission success and also will improve astronaut productivity during construction of the space station.

Cost Analysis

Like all space missions, space station construction will cost a tremendous amount of money. Thus, NASA is seeking ways of reducing costs by identifying the major parameters that could effect a lower budget.

A state-of-the-art cost analysis procedure involves making tradeoffs between activities that would be acceptable for humans versus highly dangerous tasks which are better suited to automation.[123] At present, however, many of the robotic devices postulated by this procedure do not exist or are still under development. Despite this drawback, Stuart's method is one of the most advanced proposals for projecting and analyzing space construction mission cost.

Analyses covering the sequencing of assembly tasks for the space station and actual construction activities in terms of dollars per hour or linear feet of assembly per dollar are not available in the literature. Many such cost analyses are proprietary information of NASA contractors. This area requires further investigation and development of a standardized procedure for estimating the cost of construction in space.

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[122] R. Peercy and R. Raasch, *Space Station Crew Safety Alternatives Study*, NASA Contractor Report 3857 (1985).
[123] D. Stuart.

7 RESEARCH NEEDS FOR CONSTRUCTION TECHNOLOGY IN SPACE

Over the past 30 years, the U.S. Government and most industries involved in space R&D have concentrated on sending humans into space. As a result, most of the published literature is related to rockets and propulsion in terms of space flight into low-Earth orbit or to the moon. Now that the shuttle has made it feasible for humans to travel and work in space, there is a great demand for the technology to construct facilities that will support life and equipment.

At the onset of this study, it had been assumed that the research community had established a logical, orderly program for R&D of construction in space. However, the investigation has revealed that a construction technology is only in the early stages of development and that work in this area is fragmented and incohesive. Only a few structural concepts have evolved, and their application to different aspects of construction have not been fully explored. Much more research is needed into materials design and selection, vibration and damping mechanisms, flight verification and simulation models, human productivity, and cost-effectiveness. The needs and opportunities in this field are equally great and present a major challenge to the research community.

Aerospace research into large space structures will undoubtedly see a huge boost in the near future because of the technical requirements for constructing the space station and pressure from DOD to develop SDI technology. While some research has addressed specific aspects of construction, no one to date has proposed a comprehensive research program to integrate the developing technologies. This type of plan would give direction to the long-term research objective and is a reasonable first step.

This chapter briefly summarizes the basic research needs identified for the near term. This information is taken from DOD and NASA documents as well as from interviews with NASA personnel.

Materials for Construction

General

Research into materials selection for applications in space was covered in Chapter 2. The above comment about fragmentation in space construction research also applies to the lack of a coordinated materials R&D program for large structures. However, as space station technology emerges and construction experience is gained, some of these fragmented research efforts can be expected to grow into a cohesive technology.

Composite Structures

There is a need for development of structures using polymer composites and graphite combinations as well as those using metal matrix composites. Composite structures are promising because their low mass could meet requirements for space; in addition, composites can be made to have low thermal expansion and contraction. Most work in this area is related to the aerodynamics of flying structures. Further research is needed into the properties of trusses and structures made of these materials and potential application to the space station and other facilities. Most of the R&D for these materials has focused on components of large space antennas, with emphasis on composites for joints in deployable operation modes.

Materials for Thermal Protection

Research is scarce in the area of thermal protection for assembled items in space. Protection of struts, joints, and other components should be evaluated. Thermal protection in terms of applied coatings also needs development. In addition, the research should assess possible thermal protection losses due to environmental degradation after long-term exposure to atomic oxygen (see the next section).

Protective Coatings

At low-Earth orbit, the speed of the shuttle and other orbiting objects can be up to 25,000 mph (8 km/sec). At this speed, contact with the free atomic oxygen present is frequent; the atomic oxygen has a high affinity for combining with various materials. This process causes rapid degradation of most materials, particularly polymers. Too little information is available on how atomic oxygen affects various materials--especially those used in construction.

Coatings applied to thin, flexible structures for protection against atomic oxygen need to be evaluated for degradation rate and life expectancy. Protective coatings are thin films of materials ranging from silver and gold to polymers or specialty ceramics applied either on Earth or in space to mitigate damage from exposure to the space environment. This broad area has many conceivable applications in construction technology.

Structures in Space

Low Cost Deployable Trusses

There is a great need for low-cost deployable trusses that can be automatically unfolded in space and that also may be expendable. The relationship between the compressed truss and the stresses, capabilities, and stiffness of the expanded truss with passive and active control has not been fully evaluated due to the complexity of these interactions. Therefore, this area is open to full-scale R&D.

Damage Control

Space environments can be hostile because of debris from deployed satellites and from micrometeorites. Methods of assessing truss structure stability under impact conditions from these materials have not been devised. Parameters that need to be assessed include the remaining stress capacity within a large truss structure after impact by an object and the structure's responsiveness.

Trusses Without Shuttle Constraints

The Challenger accident has made it probable that more effort will be made to deploy space construction items by traditional rocket methods. Therefore, a whole new area of automated truss deployment mechanisms could emerge. These systems could be assisted by artificial intelligence and expert systems for deployment; or, they could be self contained pressurized capsules that deploy trusses automatically.

The concept of astronaut-assisted truss assembly may lose support due to the risk factors made evident in the January 1986 shuttle accident. Although future developments may dispel this concern, it is certain that alternative approaches to construction will be seriously considered.

Structural Dynamics

Modeling Systems

As discussed earlier, it is very difficult to model and simulate on Earth the dynamic structural behavior of trusses and other structures in space. Due to the lack of gravity in space, the effects of the stiffness, rigidity, and flexibility differ greatly from Earth-type structures. Also, many of the validations made by field measurement on Earth structures are not possible in space.

The COFS space flight experiment will evaluate some of these parameters, as mentioned earlier in this report. The opportunity afforded by this structural exercise for further R&D of simulation methods could open a very large area for technological development. In particular, scaling parameters of joints, structural components, and zero-gravity simulation have a high potential for technology expansion.

Earth-Reference Structures

A whole area of research is open for Earth-reference structural simulations. The problem is that, under the influence of gravity on Earth, no one has yet devised a way to analyze space structures' dynamic behavior using scaled models. Progress in this area would greatly enhance the development and cost-effectiveness of structures to be placed in space since no zero-gravity scaling algorithm exists.

Active/Passive Controls

The combination of truss technology and artificial intelligence in active and passive control of large space structures is strictly hypothetical at present. The lack of further progress makes it difficult to model the performance of these structures once they are placed in space and also to determine what types of tradeoffs would be most cost-effective between greater stiffness in the structure and additional automatic controls for damping vibrations. Some researchers at NASA consider the issue of active control for large space structures to be irrelevant, contending that it may be possible to develop stiffness and rigidity with higher reliability for less money. This topic remains controversial.

Construction Concepts

The logical selection of sequential operations for maximum human performance, the choice of tools, and the types of mechanical assistance required while maneuvering in space and constructing large structures apparently have not been well researched at this point, especially considering the progress in other space technologies. NASA's construction research has focused mainly on antennas. Construction platforms and habitability modules are only two areas targeted for R&D; the whole arena of concept development and evaluation is waiting to be exploited.

Lunar Construction

Another area needing R&D involves the use of lunar materials for construction, an interface between robotic mechanisms and artificial intelligence, and systems carried to the moon's surface via shuttle to prepare construction sites before the astronauts arrive. This area has received only minimal attention; although there are many conceptual descriptions of lunar bases, very little in the way of actual research has been done. (Lunar construction is generally beyond the scope of this report but is mentioned occasionally to maintain a perspective for its potential role in mission support.)

Automated Construction

The whole concept of robotics/artificial intelligence/expert systems for application in construction technology has been investigated very little. Thus, methods of interfacing these systems could be the objective of a vigorous R&D program. Several technologies are based on automation (e.g., the beam builder at Marshall Space Flight Center) and could provide valuable input into this area. The Challenger accident and the possible need to construct deployable structures in space for SDI and other applications should trigger major growth in this area over the next decade.

Program Development

Potential Role for USA-CERL

Based on the information collected for this report, the responsibility for R&D addressing construction in space previously was assumed by NASA and its contractors. However, as military involvement in the space program increases (e.g., through SDI and other possible military missions), it is reasonable to predict that USACE will become more actively involved in developing construction technology.

With its long history of R&D in military construction and its various centers of expertise, USACE could have valuable input into the space construction program. Moreover, USA-CERL's mission responsibility in vertical construction makes it a logical choice for developing structures/facilities to be built in space. This projected role for USA-CERL would not appear to overlap into other agencies' territories in terms of the space construction development mission. The various missions have been defined and integrated over the past 20 years.

Another consideration is that the domain of construction in space, including that on the moon's surface, is open for development; however, NASA has not delegated responsibility to any one agency. If NASA's recent trend continues toward becoming primarily a service organization focused on mission transport into space, it is likely that another organization will be designated as lead agency for construction development.

The Air Force and Navy are mainly interested in guidance control, antenna, and satellite systems. This situation further justifies USACE's role in the construction program. As future shuttle flights are completed and the space station becomes a reality, this role probably would diminish as private contractors take over the responsibility. At present, however, the area of construction in space is open with new research opportunities for which USACE and USA-CERL could have a major impact.

Recommended Plan of Action

1. Integrated Research Program. An R&D program for construction in space should be integrated, with many disciplines focusing on single problems to achieve success. The areas most needing development are structural dynamics, composite materials, vibration control, and artificial intelligence/robotics. No one discipline, let alone a single laboratory, has enough insight to focus on the dramatic issues involved in developing a research program for structures in space; therefore, it is suggested that USA-CERL work with other Government agencies, private industry, and the academic community.

2. Aggressive R&D. Time is critical in terms of both meeting NASA's commitment for the space station and fulfilling DOD demands for SDI. With USA-CERL designated by USACE as the Army's lead agency in this effort, R&D will be coordinated and administered from a single site, which will maintain good organization and avoid duplication. USA-CERL's focus on leap-ahead technologies will be the driving force in ensuring an aggressive R&D program for construction in space.

3. Shuttle Experiment. USACE should develop a space structure experiment for flight-testing aboard the shuttle. This would be a costly endeavor, but information from Langley, Marshall, and MIT indicated that it is totally feasible and there would be a high return in terms of research benefits, visibility, and credibility.

A mission of this type would require at least 2 years of intensive planning, coordination, and research to prepare a USACE standard structures experiment. Thus, planning must begin immediately. USA-CERL would coordinate this project closely with NASA and others involved in the space program.

8 CONCLUSIONS AND RECOMMENDATIONS

The state of the art for space construction technology has been reviewed as a first step in identifying a possible mission for USACE in the development of structures to be built or deployed in low Earth orbit. Specifically, construction techniques, resources, and research directions were investigated for potential application to the space program.

Materials for construction in space have been studied to a very limited degree. Composites and polymers are promising as structural materials, but their long-term properties in a weightless environment have not been determined. In addition, most materials degrade upon exposure to solar radiation and/or atomic oxygen—both of which are present in low Earth orbit. The effects of weightlessness on material strength, flexibility, and other properties are extremely difficult to simulate on Earth due to gravity (although some ground-based "zero G" simulation facilities can provide up to 30 sec of weightlessness). Materials need to be tested in space to (1) assess their actual performance and (2) provide data for realistic simulation on Earth.

Two general types of structures are being considered in developing the baseline design for the space station: deployable and EVA assembled (erectable). A deployable structure is one that would be either partly or completely assembled on Earth and then transported into space for deployment. Most conceptual structures of this type depend heavily on automation to eliminate the need for astronaut involvement; others use a combination of robotics and human labor during EVA. The EVA-assembled structure is completely built by astronauts using components transported in the shuttle. Neither structural technology is at a stage advanced enough to recommend one or the other for the prototype station. The materials, automation, and construction techniques need much more study before a final approach can be chosen. All candidate technologies must consider the astronaut's limitations due to spacesuit inflexibility. Moreover, the effects of unattended vibration on the completed structure must be evaluated and both the logic and cost effectiveness of control mechanisms must be weighed against predicted benefits.

The 1986 Challenger disaster has renewed interest in maximizing automation for space missions in order to limit astronauts' exposure to this hazardous environment. In addition, some researchers believe it will ultimately be more cost-effective to deploy robots than the current $50,000/hr for astronaut labor. At present, however, the automation technology for constructing facilities in space has not been developed adequately. Even with the cost of training astronauts, it would be much more expensive to design and build systems meeting the unique requirements for construction in space. Nevertheless, this area could see a technology explosion within the next decade, with space specific equipment produced at a lower cost than is now possible.

Space shuttle flight STS 61B in October 1985 carried on board two experiments related to space construction: EASE and ACCESS. Since this mission represents the only construction flight test to date, the success and lessons learned have had major impact on the development of space construction technologies. As such, data from the mission serve as a baseline for future R&D. A third experiment, called SAVE, is being planned based on an evaluation of the data collected during EASE/ACCESS.

Habitability will become an important issue during and after construction of the space station. Astronauts will likely be in orbit for much longer times than in previous missions. Thus, all factors related to human function must be considered in planning the space station. The astronauts' comfort and fatigue rate will have a direct effect on their productivity, which in turn impacts cost-effectiveness.

This review has revealed that space construction technology is only in the early stages of development. The limited work devoted to this area is fragmented and incohesive. Only a few structural concepts have emerged, and their application to different facets of construction have not been fully explored. Much more R&D is needed on materials, structures, automation, and construction techniques. The needs and opportunities in this field are equally great and represent a major challenge to the research community.

In some of the intermediate stages of construction, the LSS could be unstable. Should attitude control be sought for intermediate construction stages or should the LSS be constructed in a free tumbling state? If orbital boost is required, what are the problems in the intermediate stages?

Construction in space involves many disciplines, and will provide critical service for many more disciplinary areas. The systems engineer is faced with the nearly impossible task of optimizing cost, performance, and competing disciplinary expectations. The process by which the architecture or configuration development occurs is often flawed. This process should be improved through the development of computer software to optimize cost and performance of the various disciplines involved. The use of current state-of-the-art subsystems instead of more sophisticated technology could make a project fundable. The suggested computer software could be used to evaluate system performance/cost relationships and synergistic inter-disciplinary relationships. Generally, systems engineers do not have the disciplinary depth to adequately assess all required input to their programmatic decisions. Thus, optimized software could lead to a more objective LSS design.

Based on these findings, it is recommended that a comprehensive, integrated R&D program be established to boost progress in space construction technology. USACE could be designated as lead agency for this effort, with USA-CERL serving as the center of expertise for coordinating all work with the Government (including NASA, the Navy, and the Air Force), private industry, and the academic community. USA-CERL's emphasis on leap-ahead technology would help ensure an aggressive, successful program for this unique construction environment.

Finally, it is recommended that USA-CERL plan, design, and coordinate an experiment to test a proposed USACE structure on a future shuttle flight. Only by testing materials and concepts under actual flight conditions and weightlessness will baseline data be realistic. In addition, the experiment would serve to validate or disprove simulation models, making it possible to develop good mathematical predictors for future designs. This type of mission also would have important political impact by bringing high visibility to the construction program and stimulating more interest among private industry and academia.

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